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A Study of Dimethyl Ether (DME) as an Alternative Fuel for Diesel Engine Applications

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by
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by
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Since most of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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16. Abstract

Advanced Engine Technology Ltd., in a government/industry cooperative study, investigated the feasibility of developing a cost-effective, low-emissions fuel system for the alternative fuel dimethyl ether (DME) for use in compression ignition (CI) engines. A Bosch fuel injection system for a 5.9-litre Cummins diesel engine (Dodge Ram pickup truck) was modified for use with DME.

Engine testing indicated comparable peak engine torque and power for DME and diesel operation. Peak combustion pressures, rates of combustion pressure rise, and audible engine combustion noise were low for DME operation.

ISO 8-mode steady state emissions tests indicated a reduction in oxides of nitrogen emissions (5.9 percent), particulate emissions (75 percent), ethylene and propylene emissions, and four of five unregulated emissions. Methane and total hydrocarbon (THC) emissions were low, although higher than for diesel operation. THC emissions were primarily in the form of unburned DME, which has very low toxicity and is environmentally benign relative to hydrocarbons from diesel fuel.

Further significant reductions in exhaust emissions could be achieved by optimizing the DME injection/combustion systems, incorporating an exhaust gas recirculation system, and installing a more effective exhaust catalyst. DME-fuelled CI engines may also provide a low-emissions alternative to spark ignition engines.

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16. Résumé

Advanced Engine Technology Ltd. a étudié, dans le cadre d'une recherche coopérative réunissant le gouvernement et l'industrie, la faisabilité de développer un circuit d'alimentation économique et à faible niveau d'émissions pour le diméthyléther (DME), un carburant de substitution destiné aux moteurs à allumage par compression. Un système d'injection Bosch, conçu pour un moteur diesel Cummins de 5,9 L (équipant une camionnette Dodge Ram), a été modifié pour être utilisé avec du DME.

Les essais ont révélé un couple moteur et une puissance de pointe comparables, que le moteur brûle du diesel ou du DME. Les pressions de combustion, les taux d'accroissement de pression de combustion et le bruit audible produit par la combustion étaient relativement faibles lorsque le moteur brûlait du DME.

Des essais de contrôle des émissions en huit modes de régime permanent (homologués ISO) ont révélé, dans le cas du DME, une réduction des émissions d'oxydes d'azote (5,9 p. 100), de particules (75 p. 100), d'éthylène et de propylène, et de quatre gaz non réglementés sur cinq. Les émissions de méthane et d'hydrocarbures totaux (HT) étaient faibles, mais supérieures aux émissions mesurées avec du diesel. Les émissions d'HT étaient principalement sous forme de DME imbrûlé, lequel est très peu toxique et inoffensif pour l'environnement, comparé aux hydrocarbures rejetés par le carburant diesel.

Il serait possible de diminuer encore de façon importante les émissions de gaz polluants, pour peu que l'on optimise les systèmes d'injection et de combustion du DME et que l'on dote le moteur d'un système de recyclage des gaz d'échappement et d'un catalyseur plus efficace. Les moteurs à combustion interne alimentés au DME peuvent également constituer une solution de rechange propre aux moteurs à allumage commandé.

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Diméthyléther, DME, carburant de substitution, gaz d'échappement, oxydes d'azote, NO_x, moteur diesel	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

New regulations aimed at lowering diesel engine emissions levels are being implemented in most industrialized countries. In North America, both the U.S. Environmental Protection Agency and the California Air Resources Board have adopted emissions limits covering the full range of engine sizes. As emissions standards continue to be tightened, substantial engine research and development will be required to reduce diesel engine exhaust emissions levels. Early indications are that expensive engine/fuel injection equipment modifications and emissions equipment will be required if compression ignition (CI) engines are to continue operating on conventional diesel fuel.

Alternative fuels have been considered as a replacement for diesel fuel in CI engines. One fuel in particular, dimethyl ether (DME), has shown promise. Early test results indicate that fuelling CI engines with DME instead of diesel fuel would allow the 1998 California Ultra Low Emission Vehicle emissions standard to be met without the addition of expensive emissions systems. DME operation results in near zero particulate (smoke) emissions, low oxides of nitrogen (NO_x) emissions and considerably reduced combustion noise levels.

In an effort to acquire additional information regarding the potential use of DME, the Transportation Energy Technology Division of Natural Resources Canada contracted Advanced Engine Technology Ltd. (AET) to perform a literature search in conjunction with limited in-house testing of DME (Phase I). AET was also contracted by the Transportation Development Centre (TDC) of Transport Canada to determine the safety considerations of operating a diesel engine on DME.

A Phase II federal government/industry cooperative study, based on the Phase I recommendations, was initiated. The main objectives of the Phase II study were to:

- determine the exhaust emissions characteristics of a light-duty diesel engine operating on liquid DME;
- determine the feasibility of modifying a light-duty mechanical fuel injection system to permit DME to be injected as a liquid;
- investigate combustion parameters with regard to combustion and exhaust emissions characteristics for a light-duty diesel engine operating on DME;
- determine the major safety concerns and develop preliminary safety-related design guidelines for a DME-fuelled, light-duty diesel engine vehicle fuel system;
- develop a knowledge base of DME physical properties and related fuel handling/storage considerations.

A 5.9-litre, turbocharged, intercooled Cummins diesel engine (direct injection/exhaust catalyst) from a Dodge Ram pickup truck was acquired and installed in AET's test cell #2 for test purposes. The test cell and engine fuel systems were fabricated based on the safety-related guidelines established in the DME safety study. Initially, one cylinder of the six-cylinder engine was fuelled with DME while the remaining five cylinders were fuelled with diesel fuel. Several sensors were used to allow engine temperatures and pressures to be monitored by a computer data acquisition system (DAS).

Additional safety guidelines were developed based on conclusions drawn from ongoing testing of a 5.9-litre Cummins turbocharged diesel engine operating on DME. A failure mode and effect analysis of the laboratory test engine and potential vehicle fuel system was conducted by AET for the International Energy Agency workshops on DME. The test cell fuel system was designed to minimize the potential for DME leakage into the engine's cylinders, crankcase lubricating oil sump, fuel injection pump and the atmosphere, as well as to minimize the possibility of a fire/explosion.

DME is known to adversely affect many types of plastics and rubbers, with the exception of PTFE (Teflon™) and butyl-n (Buna-N™) rubber. However, it was found that DME also generates very low temperatures upon vaporization and temperature cycling of PTFE causes embrittlement, which may lead to valve seal failure. In a fire situation both materials may melt, causing the seal to fail. It was concluded that metal-to-metal seals using non-sparking metals would be the most effective type of seal. The safety valves used on the Cummins engine were quarter-turn ball valves with graph-oil packing, chosen because of their high temperature resistance.

Based on the vehicle fuel system design, efforts were made to determine whether the injector nozzles would leak DME from the high-pressure fuel line upon engine shutdown. Preliminary injection nozzle leakdown testing was performed on new injection nozzles to determine the mass leak rate of DME past the injection nozzle needle and seat valve during the TDC DME safety study. It was determined that at pressures from 687 to 4000 kPa and temperatures from 22 to 290°C, the injection nozzle did not leak measurable quantities of DME. Efforts were undertaken to repeat the leak rate test using worn injection nozzles (90 percent of the expected useful lifetime). Significant modifications were made to the mass leak rate measuring system to allow minute rates of DME leakage to be detected and plotted versus time using a computer DAS. Efforts were also made to allow more accurate thermal cycling of the injectors. Injector temperatures could then be correlated with DME leak rates using the DAS. It is anticipated that measurable DME leakage may occur under these conditions.

Design of the DME fuel system for one cylinder of the engine was carried out using computer-aided design software. The Bosch fuel injection pump operated on diesel fuel in the normal manner; however, the diesel fuel passing through the pump was not injected into the cylinder of the engine for combustion purposes. The diesel fuel served only as a pumping

medium and was not consumed during engine operation. A shuttle valve was used to transfer the pumping action from the diesel fuel injection pump to the DME in the high-pressure fuel injection line. A high-pressure check valve was used to regulate DME flow from the low-pressure fuel supply line to the high-pressure fuel injection line.

Significant effort was directed at overcoming difficulties with DME leakage in the fuel injection system and at modifying the fuel system to provide the appropriate injection characteristics. Difficulties were encountered during much of the ongoing engine test program with DME leakage past the check valve and shuttle valve systems. Several discussions with the valve manufacturers were held to solve the DME leakage problem. Significant redesign and fabrication of the shuttle valve system was required to minimize DME leakage and provide improved sealing. The fabricated shuttle valve system, with a high-pressure lubrication system and improved check valve design, significantly improved the DME injection characteristics, allowing the engine to be operated for extended periods over the entire range of engine speeds and loads with consistent DME injection.

Significant modifications were made to the mass leak rate measuring system to allow minute rates of DME leakage to be detected. Efforts were also made to allow more accurate thermal cycling of the injectors. DME leak rate tests carried out on AET's mass leak rate measuring system using new, unused injection nozzle indicated no measurable leakage of DME at pressures up to 600 psi (room temperature conditions) and temperatures up to 550°F (150 psi). Leak rate testing using worn injection nozzles (90 percent of the expected useful lifetime) also indicated no measurable leakage of DME. It is anticipated that DME leakage past the injection nozzles into the cylinders of an engine would be insignificant, such that difficulties associated with DME vapour in the cylinders at shutdown would not be encountered.

Upon successful operation of the engine on one DME-fuelled cylinder, the remaining five cylinders were converted to operate on DME. Peak output torque/power from the DME-fuelled engine was the same as for operation on diesel fuel. In addition, low cylinder combustion pressures and rates of cylinder pressure rise were observed for DME operation. The engine was then transported to Environment Canada (EC) for AVL LIST GMBH 8 mode steady state emissions testing. Emissions testing was performed with the engine operating on DME and on diesel fuel.

Based on EC emissions results, operation on DME resulted in a reduction in regulated exhaust emissions with the exception of total hydrocarbons (THC), which were primarily in the form of unburned DME. DME is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME emissions. It is anticipated that further significant reductions in NO_x could be attained for DME operation by optimizing the fuel injection timing for low NO_x emissions, as was done by the engine manufacturer for diesel fuel operation.

Particulate matter (PM) emissions were reduced by 75 percent for DME operation. The very low particulate emission levels may be attributed to normal minute rates of crankcase lubricating oil consumption. It is anticipated that a cleaner burning crankcase lubricating oil formulation could be employed to further reduce PM and THC emissions. Low PM emissions for DME operation would reduce particulate contamination of the engine lubricating oil.

Four of five unregulated, toxic exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels, and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel are typically very low. It is anticipated that a properly sized exhaust gas oxidation catalyst would reduce the toxic non-regulated emissions.

Methane emissions (greenhouse gas) were higher for DME operation than for diesel operation. However, typical diesel engines operating on diesel fuel produce very low methane emissions. Therefore, although methane emissions increased by a factor of 24.18 for operation on DME as compared to diesel fuel, methane emissions on DME were still very low. Methane emissions could be further reduced by optimization of the fuel injection and combustion systems.

Ethylene and propylene emissions were reduced to insignificant levels for operation on DME. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were significant.

In conclusion, DME appears to be a promising alternative to diesel fuel for CI engine operation with regard to meeting future exhaust emission regulations. Significant reductions in many regulated and unregulated exhaust emissions were observed for DME operation without performing additional engine modifications directed at lowering emissions. It is anticipated that further reductions in NO_x, THC (as unburned DME), formaldehyde and methane emissions could be obtained. With regard to vehicle operation on DME, there is a need to incorporate additional fuel handling/supply safety precautions to minimize the potential for fire or explosion. DME is significantly more flammable (lower flashpoint temperature and lower auto-ignition temperature) and volatile than diesel fuel. DME fuel system components such as valves, lines and fittings should be constructed from non-sparking metals such as stainless steel or brass to minimize the possibility of generating a spark, which might lead to a fire situation. In addition, it would be necessary to ground the DME fuel tank and fuel lines to prevent electrostatic charge buildup and a potential spark discharge.

It is anticipated that further significant reductions in exhaust emissions can be realized by optimizing the DME injection/combustion systems, incorporating an exhaust gas recirculation (EGR) system and installing a more effective exhaust catalyst. Due to very low PM emissions, large quantities of EGR could be implemented for DME operation without incurring engine reliability penalties associated with high levels of PM entering the combustion chamber.

It is recommended that the following tasks be performed to further reduce the DME exhaust emissions:

1) Re-assemble the DME fuel system for the 5.9-litre Cummins engine and install the engine on the EC dynamometer in preparation for further emissions testing.

2) Install a PC-based weigh scale and associated components to allow fuel consumption rates to be determined.

3) Modify the DME injection timing to reduce NO_x emissions.

4) Modify the intake/exhaust system to incorporate EGR for NO_x reduction purposes.

5) Acquire information on various types of exhaust catalysts to determine whether there is potential to reduce NO_x, unburned DME and toxic non-regulated emissions using a specialized catalyst for DME operation.

6) Investigate the potential for reducing methane emissions.

7) Perform additional DME emissions testing implementing information and hardware arising from Tasks 1 to 5.

SOMMAIRE

La plupart des pays industrialisés mettent en place de nouveaux règlements qui visent à diminuer les niveaux d'émissions des moteurs diesel. En Amérique du Nord, l'Environmental Protection Agency (EPA) des États-Unis et le California Air Resources Board ont établi des limites d'émissions couvrant tous les types de moteurs. Ce resserrement continu des normes touchant les émissions ne peut aller sans d'intenses travaux de recherche et développement destinés à réduire les niveaux d'émission des moteurs diesel. À première vue, tout indique que, pour qu'ils puissent continuer à brûler du carburant diesel classique, les véhicules équipés d'un moteur à allumage par compression devront être l'objet de mesures coûteuses, qu'il s'agisse d'en modifier le moteur et le système d'injection ou de les doter de dispositifs antipollution.

Une solution consiste à recourir à un autre carburant, plus propre que le diesel, pour alimenter les moteurs à allumage par compression. Un carburant de substitution, le diméthyléther (DME), s'est révélé particulièrement prometteur. Selon les résultats des premiers essais, les moteurs à allumage par compression brûlant du DME plutôt que du diesel respecteraient les limites d'émissions des véhicules établies par la Californie en 1998, sans qu'il soit nécessaire de les doter de coûteux systèmes antipollution. En effet, un moteur brûlant du DME produit peu ou pas de particules (fumée), peu d'oxydes d'azote (NO_x) et ses niveaux de bruit de combustion sont considérablement réduits.

Souhaitant en savoir plus sur le potentiel du DME en tant que carburant de substitution, la Division des technologies de l'énergétique dans les transports de Ressources naturelles Canada a demandé à Advanced Engine Technology Ltd. (AET) d'effectuer une recherche documentaire et de mener des essais limités à l'interne sur le DME (phase I). AET a également reçu le mandat du Centre de développement des transports (CDT) de Transports Canada d'évaluer les incidences sur la sécurité de la conversion d'un moteur diesel au DME.

Une étude menée en commun par le gouvernement fédéral et l'industrie a ensuite été entreprise, pour donner suite aux recommandations de la phase 1. Voici les principaux objectifs assignés à cette étude :

- caractériser les émissions d'un moteur diesel pour camion léger brûlant du DME liquide;
- étudier la possibilité de modifier le système d'injection mécanique pour camion léger pour permettre l'injection de DME sous forme liquide;
- étudier les paramètres de combustion influant sur les résidus de combustion et les gaz d'échappement d'un moteur diesel pour camion léger brûlant du DME;
- déterminer les principales incidences sur la sécurité associées à l'utilisation de DME et établir des lignes directrices préliminaires visant la conception d'un circuit d'alimentation de moteur diesel pour camion léger alimenté au DME;

- constituer une base de connaissances concernant les propriétés physiques du DME et les incidences de celles-ci sur la manutention et le stockage de ce carburant.

Un moteur diesel turbocompressé Cummins de 5,9 L, à échangeur thermique (injection directe/catalyseur), qui équipe normalement une camionnette Dodge Ram, a été acheté et monté sur le banc d'essai n° 2 de AET. Pour le montage du moteur et le raccordement du circuit d'alimentation, les chercheurs ont respecté les lignes directrices en matière de sécurité issues de l'étude sur les incidences du DME sur la sécurité. Dans un premier temps, un seul des six cylindres du moteur était alimenté au DME (les cinq autres étaient alimentés au diesel). Plusieurs capteurs mesuraient les températures et les pressions à l'intérieur du moteur, et relayaient l'information à un système automatisé d'acquisition des données.

Des mesures de sécurité supplémentaires ont été élaborées à la lumière des résultats d'essais continus d'un moteur diesel turbocompressé Cummins de 5,9 L brûlant du DME. Une analyse des modes de panne et de leurs effets effectuée sur le moteur d'essai équipé de différents circuits d'alimentation potentiels a été effectuée par AET, en vue d'ateliers sur le DME organisés par l'Agence internationale de l'énergie. Le circuit d'alimentation du banc d'essai a été conçu de façon à minimiser les risques de fuite de DME dans les cylindres, la conduite de retour d'huile du carter, la pompe d'injection et l'atmosphère, et à minimiser les risques d'incendie et d'explosion.

Le DME est reconnu pour causer la détérioration de nombreux élastomères. Font exception le PTFE (Teflon^{MD}) et le butyl-n (Buna-N^{MD}). Mais il a été constaté que la vaporisation du DME s'accompagne d'une forte baisse de température et que les fluctuations répétées de température rendent le PTFE friable, ce qui compromet l'étanchéité des joints. En cas de feu, tant le PTFE que le butyl-n risquent de fondre, entraînant la perte d'étanchéité. D'où il a été conclu que les meilleurs joints seraient des joints métal/métal, pour autant que le métal utilisé ne produise pas d'étincelles. Les robinets d'arrêt d'urgence équipant le moteur Cummins étaient des robinets à boule quart-de-tour avec garnitures à l'huile graphitée, choisis en raison de leur capacité de résister à des températures élevées.

Les chercheurs ont tenté de déterminer le risque de fuite de DME par les injecteurs du circuit d'alimentation haute pression, une fois le moteur coupé. Au cours de l'étude du CDT sur les incidences du DME sur la sécurité, un nouvel injecteur a été soumis à des essais d'étanchéité qui visaient à déterminer le débit de fuite, en masse, de DME au delà de l'aiguille et du siège de l'injecteur : à des pressions de 687 à 4 000 kPa et à des températures de 22 à 290 °C, les fuites de DME se sont révélées négligeables. Les essais d'étanchéité ont alors été repris avec des injecteurs usagés (à 90 p. 100 de leur durée de vie utile). Des modifications importantes ont été apportées au système de mesure du débit de fuite en masse, afin de permettre la détection de débits minimes de fuite de DME en fonction du temps, à l'aide d'un système automatisé d'acquisition des données. Les chercheurs ont également tenté de rendre plus précis les cycles thermiques des injecteurs. La température des injecteurs pouvait alors être mise en rapport avec les débits de fuite de DME, toujours grâce au système automatisé d'acquisition des données. On pense qu'un fuite perceptible de DME est prévisible dans ces conditions.

Les chercheurs ont eu recours à un logiciel de conception assistée par ordinateur pour étudier le circuit d'alimentation en DME d'un seul cylindre du moteur. Pour ce qui est des autres cylindres fonctionnant au diesel, ils étaient alimentés de la manière habituelle par la pompe d'injection Bosch; mais le carburant diesel ainsi injecté n'était pas brûlé par le moteur : il ne servait que de support de pompage. Un piston d'injection a été utilisé pour communiquer l'effet de pompage de la pompe d'injection du carburant diesel au DME se trouvant dans la tuyauterie d'injection haute pression. Un clapet anti-retour haute pression régulait le débit de DME passant de la tuyauterie d'alimentation basse pression à la tuyauterie d'injection haute pression.

D'intenses efforts ont été déployés pour solutionner le problème des fuites de DME dans le système d'injection et pour adapter le circuit d'alimentation au DME. Pendant la plupart des essais continus sur moteur, des fuites de DME ont été constatées au delà du clapet anti-retour et du piston d'injection. Des consultations ont eu lieu avec les fabricants de ces appareils pour tenter de solutionner le problème. Il a fallu complètement repenser le piston d'injection de façon à en améliorer l'étanchéité et à minimiser ainsi les fuites de DME. Le nouveau piston, combiné à un système de lubrification haute pression et à un clapet anti-retour perfectionné, a grandement amélioré l'injection : le moteur peut tourner pendant de longues périodes, dans un large éventail de régimes et de charges, l'injection de DME demeurant constante.

Des modifications importantes ont été apportées au système de mesure du débit de fuite en masse, afin qu'il soit possible de détecter les moindres débits de fuite de DME. Des efforts ont également été déployés pour accroître la précision des cycles thermiques des injecteurs. Des mesures de débit de fuite de DME faites au moyen d'un système AET sur un injecteur neuf n'ont révélé aucune fuite mesurable de DME à des pressions allant jusqu'à 600 lb/po^2 (à température ambiante) et à des températures atteignant 550 °F (à une pression de 150 lb/po^2). Les essais de débit de fuite mettant en jeu des injecteurs usagés (à 90 p. 100 de leur durée de vie utile) n'ont pas, non plus, révélé de fuite mesurable de DME. Tout indique, donc, que les fuites de DME dans les cylindres, au delà des injecteurs, seraient négligeables, et qu'il n'y a pas lieu de craindre des problèmes associés à la présence de vapeur de DME dans les cylindres, une fois le moteur coupé.

L'essai du moteur à un cylindre alimenté au DME ayant été concluant, les cinq autres cylindres ont été convertis au DME. Le couple moteur et la puissance de pointe du moteur «tout DME» se sont avérés les mêmes que lorsque le moteur brûlait du carburant diesel. De plus, les pressions de combustion et les taux d'accroissement de la pression dans les cylindres étaient faibles. Le moteur a alors été transporté aux installations d'Environnement Canada (EC) pour y subir l'essai de contrôle des émissions en régime permanent selon huit modes conçu par AVL LIST GMBH. Le moteur a été mis à l'essai alors qu'il brûlait tour à tour du DME et du diesel.

Selon les résultats des essais menés dans les installations d'EC, le moteur brûlant du DME rejette moins de gaz d'échappement réglementés, si ce n'est des hydrocarbures totaux, qui se présentent surtout sous la forme de DME imbrûlé. Le DME est considéré comme étant très peu toxique et inoffensif pour l'environnement. Des recherches supplémentaires sur les catalyseurs pourraient ouvrir la voie à une réduction des émissions de DME imbrûlé. D'autres diminutions importantes

des émissions de NO_x seraient possibles, pour peu que l'on optimise l'avance à l'injection en fonction d'une diminution des émissions de NO_x, comme l'a fait le fabricant du moteur pour mieux l'adapter à la combustion de diesel.

Le moteur fonctionnant au DME a émis 75 p. 100 moins de particules que lorsqu'il brûlait du diesel. Ces niveaux très faibles peuvent être attribués à la consommation minime d'huile de lubrification. On peut penser que l'utilisation d'une huile de lubrification produisant moins de résidus en brûlant réduirait encore plus les émissions de particules et de HT. En outre, le moteur alimenté en DME émettant peu de particules, il s'ensuivrait une diminution de la contamination de l'huile de lubrification par des particules.

Sur cinq gaz d'échappement toxiques non réglementés mesurés au cours des essais, quatre ont été substantiellement réduits lorsque le moteur brûlait du DME. Ainsi, les émissions d'acétaldéhyde ont été réduites de 79 p. 100, celles d'acétone, de 77 p. 100, et celles d'acrylaldéhyde et de propionaldéhyde étaient devenues négligeables. Quant aux émissions de formaldéhyde, elles ont augmenté de 382 p. 100; il faut toutefois noter que les émissions de formaldéhyde sont toujours très faibles de la part de moteurs brûlant du carburant diesel. Un convertisseur catalytique d'oxydation correctement dimensionné devrait permettre de réduire les émissions toxiques non réglementées.

Les émissions de méthane (gaz à effet de serre) ont été plus importantes dans le cas du DME que du carburant diesel. Mais, encore une fois, les moteurs diesel ordinaires qui brûlent du carburant diesel rejettent très peu de méthane. Donc, les émissions de méthane étaient peut-être 24,18 fois plus importantes lorsque le moteur brûlait du DME plutôt que du diesel, mais elles étaient tout de même très faibles. Il serait possible de réduire les émissions de méthane en optimisant les systèmes d'injection et de combustion du carburant.

Les émissions d'éthylène et de propylène ont été abaissées à des niveaux négligeables dans le cas du DME. Par contraste, les émissions combinées d'éthylène et de propylène (des composants de l'ozone troposphérique) étaient importantes dans le cas du carburant diesel.

En conclusion, le DME semble constituer une solution d'avenir pour le remplacement du diesel dans les moteurs à combustion interne, notamment dans la perspective de la conformité aux nouvelles règles antipollution. Les essais ont révélé d'importantes réductions des émissions de nombreux gaz d'échappement réglementés et non réglementés par le moteur brûlant du DME, sans que le moteur comme tel ait été modifié. Et il est pensable que l'on puisse réduire encore plus les émissions de NO_x, de HT (sous forme de DME imbrûlé), de formaldéhyde et de méthane. Pour ce qui est de la conduite d'un véhicule mû au DME, d'autres mesures de sécurité s'imposent pour la manutention et la distribution du carburant, afin de minimiser les risques d'incendie et d'explosion. En effet, le DME est beaucoup plus inflammable et volatil que le diesel (son point d'éclair et sa température d'auto-inflammation sont plus bas). Les composants du circuit d'alimentation en carburant DME, comme les robinets, les tuyaux et les raccords devraient être fabriqués de métal ne produisant pas d'étincelles, comme l'acier inoxydable ou le laiton, de façon à réduire au minimum le risque d'étincelles pouvant déclencher un incendie.

Il y aurait lieu, en outre, de mettre à la masse le réservoir de carburant DME et les circuits de distribution afin d'empêcher la formation d'une charge électrostatique et le jaillissement potentiel d'une étincelle.

D'autres réductions importantes des gaz d'échappement sont à prévoir, à la faveur d'une optimisation des systèmes d'injection et de combustion du DME, de l'ajout d'un système de recyclage des gaz d'échappement (RGE) et de l'installation d'un catalyseur plus efficace. Étant donné les très faibles quantités de particules rejetées, il serait possible de recycler une grande proportion des gaz d'échappement sans nuire à la fiabilité du moteur; le bon fonctionnement du moteur est en effet compromis lorsque de grandes quantités de particules pénètrent dans la chambre de combustion.

Les mesures ci-après sont recommandées pour réduire encore plus les gaz d'échappement produits par des moteurs brûlant du DME :

1) Monter de nouveau le circuit d'alimentation en carburant DME pour le moteur Cummins 5,9 L et installer le moteur sur le dynamomètre d'EC en prévision d'autres essais de contrôle des émissions.

2) Installer un dispositif de pesage piloté par PC et les composants connexes, pour la mesure des taux de consommation de carburant.

3) Modifier l'avance à l'injection du DME de façon à réduire les émissions de NO_x.

4) Modifier le système d'admission et d'échappement pour y incorporer un mécanisme de RGE afin de réduire les émissions de NO_x.

5) Obtenir des données sur divers types de catalyseurs de gaz d'échappement, afin de déterminer s'il existe un modèle adapté au DME, capable de réduire les émissions de NO_x, d'imbrûlés et de gaz non réglementés.

6) Étudier la possibilité de réduire les émissions de méthane.

7) Reprendre les essais de contrôle des émissions de moteurs brûlant du DME, en tirant parti de l'information et du matériel nouveaux découlant de l'exécution des tâches 1 à 5.

TABLE OF CONTENTS

1 INTRODUCTION 1

2 WORK ACCOMPLISHED 2

Section I Engine Installation

2.1 Install Cummins B Series Diesel Engine 2
2.2 Measure Steady State/Transient Emissions 3
2.3 Instrument and Install Prototype DME Fuel System to One Cylinder and Carry Out Preliminary Optimization Study 4
2.4 Document Results in Part I Interim Report 7

Section II Final Optimization - Engine/Dynamometer

2.5 Prepare Engine for Safe Emissions Testing with DME Fuel System 7
2.6 Measure Steady State Emissions and Continue Optimization 8
2.7 Measure Transient Emissions and Continue Optimization Study 11
2.8 Document Results in Part II Interim Report 11

Section III A Study of Specific Concerns of DME as an Alternative Fuel for Diesel Engine Applications

2.9 From a Design Guidelines Perspective, Complete the Failure Mode and Effect Analysis (FMEA) for the Proposed Vehicular DME Fuel System 12
2.10 Carry Out Leak Rate Tests on Leak Rate Test Rig with Worn Injection Nozzles 14
2.11 Research and Fabricate a Prototype Fuel System Purge Tank 15
2.12 Report Complete Study Findings 15

3 STUDY CONCLUSIONS 15

4 CONCLUDING DISCUSSION 17

5 RECOMMENDATIONS FOR FOLLOW-ON WORK 19

REFERENCES 21

APPENDICES

Appendix A Comparison of Physical and Chemical Properties for DME, Propane and Diesel Fuel

Appendix B Photographic Documentation of AET Research Engine/DME Apparatus

Appendix C AET DME/Diesel Fuel Shuttle Valve

Appendix D Comparison of Cylinder Pressure and Rates of Cylinder Pressure Rise for DME and Diesel Operation

Appendix E AVL 8 Mode Emissions Test Engine Load and Speed Specifications

Appendix F Failure Mode and Effect Analysis (FMEA) of a Dimethylether (DME) Fuel System for Light-Duty Vehicle Applications

Appendix G AVL LIST GMBH Report No. BE 0472 Design Guidelines for Dimethyl Ether Injection Systems

LIST OF TABLES

Table 1 EPA Heavy-Duty Transient Regulated Emissions Test Results for 5.9-Litre Cummins (with Oxidation Catalyst) Engine Fuelled with Diesel Fuel 3

Table 2 Regulated Emissions Results for 5.9-Litre Cummins (with Oxidation Catalyst) Engine Fuelled with DME and Diesel Fuel 10

Table 3 Unregulated Emissio-ns Results for 5.9-Litre Cummins (with Oxidation Catalyst) Engine Fuelled with DME and Diesel Fuel 10

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AET	Advanced Engine Technology Ltd.
AVL	AVL LIST GMBH
BTDC	Before Top Dead Centre
CI	Compression Ignition
CO	Carbon Monoxide (If BS precedes CO, it refers to Brake Specific CO)
CO_2	Carbon Dioxide (If BS precedes CO_2, it refers to Brake Specific CO_2)
DAS	Data Acquisition System
DME	Dimethyl Ether
EC	Environment Canada
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
FMEA	Failure Mode and Effect Analysis
g/bhp-hr	Grams per Brake Horsepower Hour
IEA	International Energy Agency
NO_x	Oxides of Nitrogen (If BS precedes NO_x, it refers to Brake Specific NO_x)
NPT	National Pipe Thread
PM	Pariculate Matter (If BS precedes PM, it refers to Brake Specific PM)
TDC	Transportation Development Centre
THC	Total (Unburned) Hydrocarbons (If BS precedes HC, it refers to Brake Specific HC)

1. INTRODUCTION

New regulations aimed at lowering diesel engine emissions levels are being implemented in most industrialized countries. In North America, both the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board have adopted emissions limits covering the full range of engine sizes. As emissions standards continue to be tightened, substantial engine research and development will be required to reduce engine exhaust emissions levels. Early indications are that expensive engine/fuel injection equipment modifications and emissions equipment will be required if compression ignition (CI) engines are to continue operating on conventional diesel fuel.

Alternative fuels have been considered as potential replacements or supplements for diesel fuel in CI engines. One fuel in particular, dimethyl ether (DME), has shown promise [1][2][3][4]. A comparison of the physical and chemical properties of DME, diesel fuel and propane is provided in Appendix A. Early test results indicate that fuelling CI engines with DME instead of diesel fuel would allow the 1998 California Ultra Low Emission Vehicle emissions requirements to be met without the addition of expensive emissions systems. Of particular relevance is its almost smokeless operation, low oxides of nitrogen (NO_x) emissions and considerably reduced noise levels.

Combining the inherently low exhaust emissions of DME with the fuel consumption benefits of CI engines in a simple engine design would be a significant step toward a cost-effective solution in a number of transportation areas that require low exhaust emissions. Low noise levels and reduced engine weight would also be particularly attractive for hybrid vehicle technology.

In an effort to acquire additional information regarding the potential use of DME, the Transportation Energy Technology Division of Natural Resources Canada contracted Advanced Engine Technology Ltd. (AET) to perform a literature search in conjunction with limited in-house testing of DME (Phase I)[5]. In addition, a DME fuel safety study was undertaken for the Transportation Development Centre (TDC) of Transport Canada to verify the major safety concerns related to DME and develop a set of preliminary guidelines for an automotive fuel system employing DME [6][7]. A Phase II federal government/industry cooperative study, based on the Phase I recommendations, was initiated.

The main objectives of the Phase II study were to:

- determine the exhaust emissions characteristics of a light-duty diesel engine operating on liquid DME;
- determine the feasibility of modifying a light-duty mechanical fuel injection system to permit DME to be injected as a liquid;

- investigate combustion parameters with regard to combustion and exhaust emissions characteristics for a light-duty diesel engine operating on DME;

- determine the major safety concerns and develop preliminary safety-related design guidelines for a DME-fuelled, light-duty diesel engine vehicle fuel system;

- develop a knowledge base of DME physical properties and related fuel handling/storage considerations.

A 5.9-litre, turbocharged, intercooled, Cummins diesel engine (direct injection/exhaust catalyst) from a Dodge Ram pickup truck was acquired and installed in AET's test cell #2 for test purposes (please refer to Appendix B, Figures B-1 and B-2). Initially, one cylinder of the six-cylinder engine was fuelled with DME while the remaining five cylinders were fuelled with diesel fuel. Several sensors were used to allow engine temperatures and pressures to be monitored by a computer data acquisition system (DAS). Upon successful operation of the engine on one DME-fuelled cylinder, the remaining five cylinders were converted to operate on DME. The engine was then transported to Environment Canada for AVL LIST GMBH (AVL) 8 mode steady state emissions testing. Emissions testing was performed with the engine operating on DME and on diesel fuel.

2. WORK ACCOMPLISHED

SECTION I ENGINE INSTALLATION

2.1 Install Cummins B Series Diesel Engine

A support stand was fabricated on which to mount the engine/dynamometer. The Cummins 5.9-litre engine was coupled to an automotive-type water brake dynamometer using a vibration damping coupling. Upon shakedown testing it was determined that the dynamometer aluminum casting had porosity problems in a few areas and as such was deemed unsuitable for loading the test engine without substantial modifications. An eddy current dynamometer was acquired to replace the water brake dynamometer and another engine/dynamometer support stand fabricated.

A closed-loop cooling system for the eddy current dynamometer was fabricated. It consisted of an in-ground coolant reservoir, a large radiator/cooling fan, two cooling water circulation pumps/motors, hoses and support stands. Unanticipated difficulties with the eddy current dynamometer drainage system were encountered that required significant modifications to the closed-loop cooling system. Modifications to the dynamometer controller were also required to allow engine loading within the constraints of the test program.

Two AET DAS's were used to collect data from the test cell instrumentation. Fourteen

thermocouples were used to measure engine, dynamometer and ambient temperatures. Engine torque was measured using a load cell. Cylinder #1 of the Cummins engine was instrumented with a piezoelectric pressure transducer to measure cylinder combustion pressures. Cylinder pressures were then correlated to crankshaft angular position using an optical encoder mounted on the crankshaft. The Bosch P7100 fuel injection nozzle in Cylinder #1 was instrumented with a needle lift proximity sensor by an external instrumentation source. The needle lift sensor was used to correlate the injection nozzle needle opening period with crankshaft angular position. Modifications were made to the high-pressure fuel injection line on Cylinder #1, allowing a piezoelectric pressure transducer to be installed in the line near the injection nozzle. The fuel line pressure transducer was used to correlate pressure waveforms in the injection line with crankshaft angular position. Computer software to operate the two DAS's was developed in-house.

2.2 Measure Steady State/Transient Emissions

During the interim between the water brake dynamometer shakedown tests and installation of the eddy current dynamometer, the Cummins B Series engine was shipped to the Mobile Sources Emissions Division of Environment Canada (EC) for emissions testing. The engine was tested at EC with all six cylinders operating on diesel fuel. EC emissions results are compared to the Cummins emissions results for an EPA heavy-duty transient test cycle in Table 1.

Test Location	BSHC (g/bhp-hr)	BSNO$_x$ (g/bhp-hr)	BSCO (g/bhp-hr)	BSCO$_2$ (g/bhp-hr)	BSPM (g/bhp-hr)
Cummins	0.18	4.78	0.91	564	0.07
EC	0.22	8.31	2.45	660	0.19

Table 1 EPA Heavy-Duty Transient Regulated Emissions Test Results for 5.9-Litre Cummins (with Oxidation Catalyst) Engine Fuelled with Diesel Fuel

The emissions results in Table 1 are composite numbers, approximated by 1/7 of the value of the cold start emissions results and 6/7 of the value of the hot start emissions results. EC emissions results were greater than the Cummins emissions results, particularly for NO_x, carbon monoxide (CO) and particulate matter (PM). This discrepancy may be due to difficulties encountered at EC with the intake aftercooler located between the turbocharger and the engine cylinder head on the inlet air system.

2.3 Instrument and Install Prototype DME Fuel System to One Cylinder and Carry Out Preliminary Optimization Study

Design discussions were carried out with DuPont representatives regarding the components required for AET's laboratory DME fuel system with regard to safety considerations. Additional information was gathered through discussions with other parties involved with DME and from literature relating to DME fuelling of diesel engines. Cadkey drawings of AET's DME engine/test cell/storage facilities were made and submitted to DuPont representatives for approval. Upon completion of the engine/test cell DME fuel systems, a comprehensive safety audit of AET was organized and carried out by DuPont.

The DME fuel system (low pressure side) consisted of a high-pressure DME storage reservoir, a helium pressure tank/regulator, high-pressure copper fuel lines, check valves, blow off valves, shut-off valves, couplers and two fire-safe emergency shut-off valves. Regulated high pressure helium (20 bar) was forced into the dual-fitting DME fuel reservoir, thereby pressurizing the DME in the tank and low-pressure lines leading to the engine. Helium was employed because of its low solubility in DME. Blow off valves were installed on the fuel reservoir and copper fuel lines to release DME to the atmosphere in a controlled manner during a fire, thereby minimizing the possibility of an explosion. Fire-safe emergency shut-off valves were installed (one on the fuel reservoir, one on the engine) to allow the operator to stop the flow of DME to the engine and laboratory during a fire or potential fire situation. In addition, a large carbon dioxide (CO_2) fire extinguisher was plumbed from outside the test cell to a diffuser just above the DME fuel system on Cylinder #1 as an additional safety feature.

The following design guidelines were adhered to during fabrication of the laboratory DME fuel system:

- Non-sparking metals (stainless or brass) were used for the DME fuel tank, fuel line fittings and valves to eliminate spark generation from wrenches, which might lead to a fire situation.

- The DME fuel tank, fuel line and engine were grounded to grounding rods to prevent electrostatic charge buildup and discharge, thereby further minimizing the possibility of a charge buildup and the occurrence of a spark that might lead to a fire situation.

- Substantial over-pressure capability was designed into all DME fuel system components (based on a normal DME operating pressure of up to 600 psi) to allow for pressure increases generated by temperature fluctuations in the fuel system and the high thermal expansion rates of DME.

- A protective metal covering was placed along the DME fuel line to prevent possible puncture of the line and the potential for a fire situation.

- Remotely activated, fire-safe emergency shut-off valves were used to allow the operator to shut off the DME supply in the event of a fuel line rupture and/or fire.

- A blowdown valve was installed on the DME fuel tank to vent the DME during a fire, thereby preventing an explosion of the fuel tank from over-pressurization caused by excessive temperatures (fire).

- Water spray was made available to cool the DME fuel tank in the event of a fire. Cooling the tank would reduce the DME pressure in the tank and consequently reduce the rate at which DME would be vented through the fuel tank blowdown valve.

- DME exiting the fuel injection nozzle return line was vented to atmosphere well away from the high-temperature engine components and other sources of ignition.

Design of the DME fuel system for one cylinder of the engine was carried out using computer aided design software. The Bosch fuel injection pump operated on diesel fuel in the normal manner; however, the diesel fuel passing through the pump was not injected into the cylinder of the engine for combustion purposes. The diesel fuel served only as a pumping medium and was not consumed during engine operation. A shuttle valve was used to transfer the pumping action from the diesel fuel injection pump to the DME in the high-pressure fuel injection line. A high-pressure check valve was used to regulate DME flow from the low-pressure fuel supply line to the high-pressure fuel injection line. Numerous discussions were held with Robert Bosch Corporation to assist with the design/fabrication of the fuel system shuttle valve.

Difficulties were encountered during much of the early portions of the engine test program as DME leakage past the check valve and shuttle valve systems resulted in poor injection characteristics, vapour lock in the injection pump, and sporadic engine operation.

In addition to DME leakage, difficulties were encountered with breakage of the shuttle valve return spring. It was hypothesized that the DME was vaporizing for a brief period during closing of the shuttle valve resulting in momentary low temperatures around the valve spring. The low temperatures, followed by warmer temperatures once the fuel line filled with DME liquid under pressure, would cause thermal cycling of the spring and possible thermal fatigue/cracking/failure. Efforts were directed at acquiring a larger diameter check valve, which would allow DME liquid to flow from the DME supply line to the shuttle valve area more rapidly, thereby minimizing DME vaporization in the high-pressure fuel line.

Based on discussions with check valve manufacturers, it was concluded that a larger check valve with higher cracking pressures and greater high-frequency response would improve the valve's operation and engine performance. Modifications were made to the fuel system to incorporate a larger check valve. No noticeable improvement in engine operation was observed.

Further investigation indicated that DME leakage was also occurring with the new check valves. Substantial additional effort was required to select a suitable check valve. Difficulties were encountered in finding an appropriate check valve due to the size, leak rate and pressure characteristics required. Several automotive-type check valves were tested, each iteration requiring significant effort to modify the fuel system for each check valve evaluation. The automotive-type check valve was replaced with a high flow rate, high-pressure, aerospace check valve to reduce the rates of DME leakage and increase the longevity of the check valve system. No difficulties were encountered throughout the remainder of the test program with the aerospace check valves.

Design modifications were made to eliminate DME leakage past the shuttle valve. Initial design modifications reduced leakage past the shuttle valve, allowing brief engine operation on DME. Numerous attempts to modify the original shuttle valve concept to improve sealing resulted in only minor success. It was concluded that excessive DME leakage was due to the clearances between the shuttle valve and valve body as supplied by Bosch. To improve sealing, additional shuttle valves with reduced clearances were fabricated by Bosch and forwarded to AET to replace the original shuttle valves. No significant improvements, however, were observed.

Further discussions were held with Bosch to acquire a shuttle valve with the appropriate clearances. It was concluded that Bosch was not in a position to make a limited quantity of prototype shuttle valves with the required clearances. It was agreed that Bosch would send AET an existing fuel injection system component with the desired clearances. AET would then fabricate a shuttle valve/valve body from the Bosch component. The AET fabricated shuttle valve was designed with a significantly larger diameter than the Bosch fabricated shuttle valves, thereby reducing the shuttle valve travel required to displace the DME. It was anticipated that the reduction in shuttle valve travel would be beneficial in terms of decreasing the shuttle valve's lubrication requirements and reducing shuttle valve and return spring stresses.

A high-pressure lubrication system was fabricated to lubricate the shuttle valve to reduce the anticipated high wear rates associated with exposure of the shuttle valve to neat DME without lubricating additives. In addition to improving the lubricity of the DME, the lubrication system improved sealing around the shuttle valve, check valve and injection nozzle needle/seat areas. The lubricant (diesel fuel) was forced into the small clearance gap of the shuttle valve under significant pressure, thereby acting as a barrier to DME migration through the shuttle valve clearance gap.

The fabricated shuttle valve system (please refer to Appendix C), with its high-pressure lubrication system and improved check valve design, significantly improved the DME injection characteristics, allowing the engine to be operated for extended periods of time over the entire range of engine speeds and a wide range of loads with consistent DME injection. However, output torque from the DME-fuelled cylinder was approximately the same as for the diesel-

fuelled cylinders only at engine speeds below 1500 rpm. At higher engine speeds, output torque decreased as a result of a limitation in the quantity of fuel that could be injected into the cylinder and inadequate fuel injection timing. It was concluded, based on cylinder pressure, fuel line pressure traces and needle lift traces, that additional work would be required to provide optimal injection timing and increased delivery quantities (injection nozzle orifice diameters) over the entire range of engine speed/load conditions.

2.4 Document Results in Section I Interim Report

The results of Part I were documented as part of a TDC report entitled *Safety Considerations of Dimethyl Ether (DME) as an Alternative Diesel Fuel*, TP 13456E.

SECTION II FINAL OPTIMIZATION - ENGINE/DYNAMOMETER

2.5 Prepare Engine for Safe Emissions Testing with DME Fuel System

As indicated in Section I, AET was contracted by TDC to verify the major safety concerns associated with operating an engine on DME and to develop a set of preliminary safety guidelines for an automotive fuel system designed for use with DME as an alternative diesel fuel. Because DME is more flammable (lower flashpoint and higher vapour pressure) than diesel fuel, engine operation on DME requires special safety precautions to minimize the potential for a fire or explosion. The DME safety-related study concentrated on an evaluation of different types of valves for the automotive fuel system, in particular DME fuel system emergency shutoff valves and DME fuel injection system needle valves in fuel injection system nozzles.

An AET representative attended three International Energy Agency (IEA) workshops on DME. A Failure Mode and Effect Analysis (FMEA) was performed for AET's DME fuel system and compared to other IEA workshop participants' DME fuel systems. Significant effort was directed toward preparing an FMEA for a DME fuel system to be employed for light-duty vehicle applications. The vehicle fuel system was designed to minimize the potential for DME leakage into the engine's cylinders, crankcase lubricating oil sump, fuel injection pump and the atmosphere, as well as minimize the possibility of a fire/explosion. Cadkey drawings of the DME fuel injection system boundary conditions, the vehicle fuel system and an engine/fuel state summary were prepared for submission to IEA. Additional preparation included a summary of implicit assumptions regarding the DME fuel system and tables describing the function, potential failure and cause/effect of failures related to all DME vehicular fuel system components (please refer to section 2.9 for additional information).

Based on the aforementioned DME safety study and DME fuel system FMEA, modifications were made to AET's test cell DME fuel system to ensure that appropriate safety guidelines were met. These guidelines were also followed during fabrication of the DME fuel system for emissions testing at EC.

2.6 Measure Steady State Emissions and Continue Optimization

Preliminary test results with Cylinder #1 operating on DME indicated that faster rates of DME injection would be required at high engine speeds as well as changes in injection timing to maintain the output power characteristics of the engine. The diameter of the orifices in the Cylinder #1 injection nozzle were enlarged to increase the flow of DME through the injection nozzle. Several iterations were required to optimize the injection nozzle orifice diameter and injection timing for low-speed and high-speed engine operation.

Upon completion of the optimization process for Cylinder #1, modifications were made to the engine/DME fuel system to allow the remaining five cylinders to operate on DME (please refer to Appendix B, Figures B-4 and B-5). Dynamometer testing of the Cummins engine operating with all six cylinders on the optimized DME fuel system confirmed that satisfactory engine power could be obtained at all engine speeds. The injection timing for DME operation was optimized to provide near peak power, corresponding to high thermal efficiency and low fuel consumption rates, while maintaining moderate combustion pressures and low rates of combustion pressure (please refer to Appendix D, Figures D-1 through D-4). Since the Bosch mechanical fuel injection pump did not have variable injection timing with regard to engine speed, it was necessary to shut the engine down and re-time the injection pump for varying load and speed conditions. To simplify testing, two DME injection timings were used during the operability and emissions tests: 10° before top dead centre (BTDC) for low engine speeds and 20° BTDC for high engine speeds. Newer Bosch electronic fuel injection pump systems have variable timing capabilities; however, it was not within the scope of the project to try to retrofit the engine with this type of system.

EC personnel visited AET to review the engine test program requirements, the test schedule for emissions testing at EC, DME fuel safety, DME fuel storage/handling requirements, the AET DME fuel system and the proposed DME fuel system at EC. AET personnel visited EC on several occasions to review installation of the test apparatus, including the engine, a 2000-lb. high-pressure reservoir (1000 lb. of DME) and the copper fuel lines connecting the reservoir to the engine (please refer to Appendix B, Figure B-3). The test cell ventilation system was also evaluated in terms of safety. A comprehensive safety audit of EC was carried out by AET upon completion of the EC DME engine/test cell fuel systems.

Engine/dynamometer shakedown testing at EC indicated significant difficulties with the water brake dynamometer. AET offered advice to EC personnel with regard to repairing the dynamometer, based on similar experiences at AET with a water brake dynamometer used in another project. Upon repair of the dynamometer by EC personnel, engine/dynamometer/test cell shakedown testing was performed. Minor difficulties were encountered with DME leakage at the fittings in the copper fuel line running through the test cell area.

Additional difficulties with the EC dynamometer were encountered with regard to maintaining the required load and speed for Mode 5 of the AVL 8 mode emissions test (please refer to

Appendix E for loads/speeds). To rectify the dynamometer difficulties it was necessary to operate the Cummins engine for extended lengths of time at Mode 5 conditions (low load/high speed). During this time, injector nozzle tip difficulties (scored/seized needles) were encountered as a result of the low lubricity of DME and extended Mode 5 operation. During Mode 5 operation the opening/closing frequency of the injector needles was high because of the high engine speed; however, the flow of DME over the injector needles for lubrication was low because of the low load. The amount of DME present for lubrication during each injector needle opening/closing period was therefore minimal, leading to insufficient lubrication and seizure. Six additional nozzle tips were acquired and the orifices enlarged to the desired diameter.

To complete the test program as rapidly as possible with minimal risk of subsequent nozzle tip difficulties, AET designed and fabricated a pressurized DME injector return flow system to improve lubrication of the injector needle. The pressurized system maintained the DME as a liquid as it returned from the nozzle tip. The previous non-pressurized system allowed the DME return from the injector to vaporize along the bearing area of the needle. It was anticipated that maintaining the DME as a liquid along the bearing area of the needle would provide significantly improved needle lubrication. No further needle lubrication difficulties were encountered during the remainder of the test program.

The AVL 8 mode emissions test was performed for the 5.9-litre Cummins engine operating on DME and on diesel fuel with the standard oxidation catalyst for this engine installed in the exhaust system. Three emissions tests were performed on DME (please refer to Appendix B, Figures B-6 through B-8). Upon completion of the DME tests, the DME fuel system was removed and the original diesel fuel system components were re-installed. Two emissions tests were then performed on diesel fuel for comparison purposes. Data collected during the tests included: 1) regulated and non-regulated exhaust emissions; 2) exhaust temperatures; 3) coolant temperature; 4) crankcase lubricating oil temperature; 5) cylinder pressure; 6) fuel line pressure; and 7) fuel injector needle lift.

The injection timing for DME operation was optimized to provide near peak power, corresponding to high thermal efficiency and low fuel consumption rates, while maintaining moderate combustion pressures and low rates of combustion pressure rise. It was anticipated that the diesel fuel injection timing had been optimized similarly. However, during diesel emissions testing it became evident, based on combustion pressure traces, that the manufacturer (Cummins) had not optimized the injection timing in the aforementioned manner. The diesel injection timing was significantly retarded by the manufacturer to produce low NO_x emissions (especially at high engine speeds) at the expense of thermal efficiency, power and fuel consumption rates.

Time constraints prevented the engine from being re-tested on DME with the injection timing retarded to better correlate with the diesel fuel tests. It is anticipated that significant additional NO_x reductions would have been obtained for operation on DME with retarded

injection timing.

Table 2 summarizes the overall average for the regulated exhaust emissions with the engine operating on DME and diesel fuel.

Fuel	CO (g/bhp-hr)	CO_2 (g/bhp-hr)	NO_x (g/bhp-hr)	THC (g/bhp-hr)	PM (g/bhp-hr)
DME	0.253	544.7	3.33	0.427	0.02
Diesel	0.445	588.5	3.54	0.180	0.08

Table 2: Regulated Emissions Results for 5.9-Litre Cummins (with Oxidation Catalyst) Engine Fuelled with DME and Diesel Fuel

With regard to regulated emission results, engine operation on DME reduced CO emissions from 0.445 to 0.253 g/bhp-hr (43 percent reduction). CO_2 emissions were reduced from 588.5 to 544.7 g/bhp-hr (7.4 percent reduction). NO_x emissions were reduced from 3.54 to 3.33 g/bhp-hr (5.9 percent reduction). Further reductions in NO_x (DME) could be attained by optimizing the timing for low NO_x emissions as was done by the engine manufacturer for diesel fuel operation. Total hydrocarbon (THC) emissions increased from 0.18 to 0.427 g/bhp-hr. (237 percent increase) for DME operation. THC emissions for DME operation were primarily unburned DME. DME is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME and methane emissions. PM emissions were reduced from 0.08 to 0.02 g/bhp-hr (75 percent reduction).

Table 3 summarizes the ozone reactivity and toxicity values for unregulated emissions compounds.

Compound	Percent Change in Emissions for DME Operation	Reactivity (grams of ozone per gram of compound)	National Occupational Standards Permissible Exposure Limit (over 8 hr period)
Formaldehyde	(+) 382%	7.15	3 ppm
Acetaldehyde	- 79%	5.52	200 ppm
Propionaldehyde	- 99%	6.53	Not available
Acrolein	- 99%	6.77	0.1 ppm
Acetone	- 77%	0.56	1000 ppm

Table 3: Unregulated Emissions Results for 5.9-Litre Cummins Engine (with Oxidation Catalyst) Fuelled with DME and Diesel Fuel

With regard to unregulated emissions, absolute emissions values in g/bhp-hr cannot be reported because of emissions collection difficulties at EC. However, the results can be compared between DME and diesel fuel on a relative basis. Four of five unregulated, toxic exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel is typically very low. It is anticipated that a more appropriately sized oxidation catalyst in the exhaust system would significantly reduce the toxic exhaust emissions.

Methane emissions (greenhouse gas) increased by a factor of 24.18 for DME as compared to diesel fuel. However, it should be noted that although methane emissions were higher than for diesel operation, typically diesel engines operating on diesel fuel produce very low methane emissions. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were substantial. Ethylene and propylene emissions were reduced to insignificant levels for operation on DME.

2.7 Measure Transient Emissions and Continue Optimization Study

It was determined that operation on DME required variable injection timing with regard to engine speed. Substantial changes in injection timing were required between low-speed (10°BTDC) and high-speed (20°BTDC) operation. However, the Bosch mechanical fuel injection pump on the engine did not offer variable timing capability. It was concluded that performing a transient test with varying engine speeds and loads with a single injection timing would not provide meaningful emissions results.

Efforts made to find a solution to the variable timing difficulty indicated that significant engine modifications not within the scope of the project would be required to install a mechanical system that would support and rotate the Bosch fuel injection pump relative to the crankshaft during engine operation, thereby altering the injection timing. Retrofitting the engine with a newer Bosch electronic fuel injection pump system with variable timing capabilities was also deemed not to be within the scope of the project. This task was therefore not undertaken.

2.8 Document Results in Section II Interim Report

The results of Part II were documented as a series of interim progress reports.

SECTION III A STUDY OF SPECIFIC OF SPECIFIC CONCERNS OF DME AS AN ALTERNATIVE FUEL FOR DIESEL ENGINE APPLICATIONS

2.9 From a Design Guidelines Perspective, Complete the Failure Mode and Effect Analysis (FMEA) for the Proposed Vehicular DME Fuel System

Significant effort was directed toward further modifying the DME fuel system design based on recommendations from the FMEA workshops. The proposed DME vehicle fuel system received a favourable rating by IEA participants with regard to the FMEA risk assessment.

The following design guidelines refer to a DME fuel system based on the AET laboratory engine DME fuel system design. It is anticipated that the AET DME fuel system design would differ from other DME fuel system designs in that a small reservoir of diesel fuel or other similar fluid in terms of viscosity, density and lubricity would be employed. The reservoir of diesel fuel or similar fluid would be used to operate the injection pump and lubricate the injection system shuttle valve. A minute quantity of diesel fuel would leak past the shuttle valve to lubricate the injection nozzle needle. This minute quantity of diesel fuel would be combusted along with the DME in the engine's combustion chamber. It is anticipated that the rate of diesel fuel usage would be insignificant, such that the diesel fuel reservoir could be filled up at the same frequency as an oil level check or oil change.

Based on the FMEA study, the following guidelines should be adhered to during fabrication of a vehicle DME fuel system:

- Non-sparking metals (stainless or brass) should be used for the DME fuel tank, fuel line fittings and valves to eliminate spark generation from wrenches, which might lead to a fire situation.

- All wrenches used for assembling/disassembling the DME fuel system should be non-sparking.

- The vehicle refuelling system should have provision for grounding to the vehicle DME fuel system such that there can be no electrostatic charge potential between the vehicle and the vehicle refueling system. Electrostatic charge buildup can lead to an electrical discharge in the form of a spark, which might lead to a fire situation.

- All DME fuel system components, including the DME fuel reservoir, fuel line fittings/valves and fuel filler line, should be electrically continuous and grounded to prevent electrostatic charge buildup. Because of the poor electrical conductivity of DME, DME fuel system components are susceptible to electrostatic charge buildup. Electrostatic charge buildup on fuel system components can lead to an electrical discharge in the form of a spark, which might lead to a fire situation.

- An explosion-proof fuel pump should be employed to pump the DME from the fuel reservoir to the high-pressure fuel lines.

- National Pipe Thread fittings in the DME fuel system should not be used; instead, all fittings should be butt-welded American National Standards Institute flanges.

- A fuel storage level fill shut-off system should be employed to ensure that the reservoir is not filled above 80 percent capacity, thereby allowing room for expansion of the DME during varying ambient temperature conditions. DME has a high thermal expansion rate and it is therefore necessary to leave 20 percent additional reservoir volume to allow for DME expansion during temperature fluctuations.

- Substantial over-pressure capability must be designed into all DME fuel system components (based on a normal DME operating pressure of up to 600 psi) to allow for pressure increases generated by temperature fluctuations in the fuel system and the high thermal expansion rates of DME.

- A blowdown valve should be installed on the DME fuel tank to vent the DME during a fire, thereby preventing an explosion of the fuel tank from over-pressurization caused by excessive temperatures (fire).

- Vehicle operators should be instructed to spray the DME fuel tank with water (if available) in the event of a fire. Cooling the tank with the water spray will reduce the DME pressure in the tank and consequently reduce the rate at which DME would be vented through the fuel tank blowdown valve.

- A pressure relief valve should be installed in all locations where the DME fuel is contained, including the fuel reservoir and the fuel lines between shut-off valves. The pressure of DME in a confined space varies substantially with temperature. High temperatures including fire situations may result in excessive DME pressures and fuel system ruptures unless a pressure relief valve is installed.

- Remotely operated emergency shut-off (fire-safe) valves, constructed from DME compatible materials, should be installed to allow the operator to shut off the DME supply in the event of a fuel line rupture and/or fire.

- The DME purge tank should be located such that its vent is outside the vehicle so that DME is not vented in the area of high underhood temperatures, exhaust system components and electrical system components. During engine operation the DME in the purge tank should be combusted in the engine at a controlled rate.

- Threaded fasteners and bracketry used to attach DME fuel system components should be corrosion (salt/oxidation) resistant.

- The vehicle DME fuel tank should be corrosion (salt/oxidation) resistant and positioned such that it is not subjected to sand/salt/water.

- A protective metal covering should be placed along the DME fuel line from the fuel storage reservoir and the high-pressure injection pump to prevent possible puncture of the line and the potential for a fire situation.

- Sensors should be installed on the vehicle to warn the operator of DME leaks. DME leaks could be determined by inexpensive pressure sensors monitoring DME pressure and by a DME gas detector.

- The vehicle DME fuel system should be tested extensively for crashworthiness. It is anticipated that employing safety measures similar to those used on propane vehicles would provide a good starting point.

- Lubricating additives compatible with DME should be added to the DME to extend the life of the fuel system components, thereby reducing the potential for undesirable leaks.

- Engine overspeed protection should be employed such as an air shut-off flap in the intake air system. Leakage of DME into the engine's intake air system or cylinders due to a malfunction could cause engine overspeeding since the rate of fuel entering the engine would not be controlled. Similar circumstances with diesel fuel would be less likely to cause engine overspeeding since, unlike DME, diesel fuel does not atomize readily unless injected under high pressures.

2.10 Carry Out Leak Rate Tests on Leak Rate Test Rig with Worn Injection Nozzles

During the DME safety study contracted by TDC, a DME fuel mass leak rate measuring system was developed to determine the rate of DME leakage past the fuel injection nozzle needle and seat of the 5.9-litre Cummins engine. The injection nozzles used during this study were new (unused). It was anticipated that significant DME leak rates past the injection nozzle would result in DME entering the DME-fuelled cylinder upon engine shutdown. Upon engine startup the cylinder would be full of DME vapour, causing excessive combustion pressures, combustion knock and engine speeds.

The fuel mass leak rate measuring system consisted of a weigh scale, pressure vessel, high-pressure fuel line, fuel injection nozzle (with the return vent sealed) and thermostatically controlled heating system (please refer to Appendix B, Figures B-9 and B-10). The mass leak rate measuring system allowed the rate of DME mass loss from the injector nozzle to be determined at varying pressures and temperatures, allowing simulation of injector conditions upon engine shutdown, as well as testing at more extreme temperature/pressure conditions.

Significant modifications were made to the mass leak rate measuring system to allow minute

rates of DME leakage to be detected. Efforts were also made to allow more accurate thermal cycling of the injectors. DME leak rate tests on new, unused injection nozzles indicated no measurable leakage of DME at pressures up to 600 psi (room temperature conditions) and temperatures up to 550°F (150 psi). Leak rate testing using worn injection nozzles (90 percent of the expected useful lifetime) also indicated no measurable leakage of DME. It is anticipated that DME leakage past the injection nozzles into the cylinders of an engine would be insignificant, such that difficulties associated with DME vapour in the cylinders at shutdown would not be encountered.

2.11 Research and Fabricate a Prototype Fuel System Purge Tank

A purge tank was fabricated to collect DME vapours from the DME fuel injection system, upon engine shutdown. Several DME fuel system purge tanks were considered and evaluated using the FMEA. Upon completion of the task descibed in section 2.10, it was concluded that the DME leak rates from worn injectors (worst case) was very small, suggesting that a purge tank might not be required, particularly for applications in which the fuel system cost was a major consideration.

Because of time and budget constraints brought about by unanticipated difficulties encountered in other tasks with operation of the DME fuel system, the purge tank was not tested on the engine.

2.12 Report Complete Study Findings

The results of the study were documented as part of this report.

3. STUDY CONCLUSIONS

The following conclusions were drawn during this study.

DME Engine Operation/Emissions

- The relatively simple, low-cost DME fuel injection system provided power levels equivalent to diesel fuel operation when employed on the Cummins engine.
- Low cylinder combustion pressures and rates of cylinder pressure rise were observed for DME operation. Although the combustion pressures and rates of cylinder pressure rise for DME operation were as high or slightly higher than for diesel operation, this can be attributed to the significantly retarded injection timing employed by the engine manufacturer for diesel operation.
- PM emissions were reduced by 75 percent for DME operation. The very low PM

emissions levels may be attributed to normal minute rates of crankcase lubricating oil consumption. It is anticipated that a cleaner burning crankcase lubricating oil formulation could be employed to further reduce PM and THC emissions.

- Low PM emissions for DME operation would reduce particulate contamination of the engine lubricating oil.

- CO emissions were reduced by 43 percent for DME operation.

- CO_2 emissions were reduced 7.4 percent for DME operation.

- NO_x emissions were reduced by 5.9 percent for DME operation. It is anticipated that further significant reductions in NO_x (DME) could be attained by optimizing the timing for low NO_x emissions as was done by the engine manufacturer for diesel fuel operation.

- THC emissions increased by 237 percent for DME operation. However, THC emissions for DME operation were primarily unburned DME, which is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME and methane emissions.

- Four of five toxic unregulated exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel is typically very low. Toxic emissions including formaldehyde can be oxidized using a more appropriately sized exhaust catalyst.

- Methane emissions (greenhouse gas) were higher for DME operation than for diesel operation. However, typical diesel engines operating on diesel fuel produce very low methane emissions. Therefore, although methane emissions increased by a factor of 24.18 for operation on DME as compared to diesel fuel, methane emissions on DME were still very low. Methane emissions could be further reduced by optimization of the fuel injection and combustion systems.

- Ethylene and propylene emissions were reduced to insignificant levels for operation on DME. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were significant.

DME Fuel System

- Because DME is more flammable (lower flashpoint and higher vapour pressure) than diesel fuel, engine operation on DME requires special safety precautions to minimize the

potential for a fire or explosion.

- Metal fuel system components should be non-sparking, such as stainless steel or brass, to minimize the possibility of generating a spark that might lead to a fire situation.

- Grounding of the DME fuel tank and fuel line is required to prevent electrostatic charge buildup and discharge to minimize the possibility of generating a spark that might lead to a fire situation.

- Plastic and rubber fuel system components typically used for vehicle applications should be replaced with non-sparking metal components such as stainless steel or brass. Components that cannot be replaced with the aforementioned metals should be constructed from Teflon or Butyl-N rubber, which are chemically resistant to DME and the traces of methanol typically found in commercial DME.

- Fire-safe ball valves with graph-oil packing should be used as emergency DME shut-off valves. Graph-oil packing was recommended by DuPont because of its high temperature capabilities and resistance to temperature cycling. These types of valves are designed to withstand fire situations without allowing fuel (DME) leakage.

- New and worn Bosch fuel injection nozzles provided a good seal against DME leakage in the needle and seat areas. The effects of needle and seat wear and/or deposits in the needle and seat area on sealing were not determined.

- The small quantity of DME in the high-pressure injection line leaked through the injection nozzle return into the purge tank within a few minutes of engine shutdown, further minimizing the opportunity for DME to leak past the injection nozzle needle into the engine's cylinders.

- The fabricated shuttle valve system with a high-pressure lubrication system and improved check valve design significantly improved the DME injection characteristics, allowing the engine to be operated for extended periods of time over the entire range of engine speeds and loads with consistent DME injection.

4. CONCLUDING DISCUSSION

In conclusion, DME appears to be a promising alternative to diesel fuel for CI engine operation with regard to meeting future exhaust emissions regulations. Operation of AET's test engine on DME indicated consistent DME injection and smooth combustion at all engine speeds and loads. Peak output torque/power from the DME fuelled engine was the same as for operation on diesel fuel. In addition, low cylinder combustion pressures and rates of cylinder pressure rise were observed for DME operation.

Regulated exhaust emissions were reduced with the exception of THC, which was primarily in the form of unburned DME. DME is regarded as having very low toxicity and as being environmentally benign. Further investigation into exhaust catalysts may be beneficial in reducing unburned DME emissions. It is anticipated that further significant reductions in NO_x (DME) could be attained by optimizing the fuel injection timing for low NO_x emissions as was done by the engine manufacturer for diesel fuel operation. Further reductions in NO_x could also be realized with exhaust gas recirculation (EGR). Because of very low PM emissions, large quantities of EGR could be implemented for DME operation without incurring engine reliability penalties associated with high levels of PM entering the combustion chamber.

Four of five unregulated, toxic exhaust emissions were substantially reduced for DME operation. Acetaldehyde emissions were reduced by 79 percent, acrolein and propionaldehyde emissions were reduced to insignificant levels and acetone emissions were reduced by 77 percent. Formaldehyde emissions increased by 382 percent; however, formaldehyde emissions for diesel engines operating on diesel fuel is typically very low. It is anticipated that a properly sized exhaust gas oxidation catalyst would reduce the toxic non-regulated emissions.

Methane emissions (greenhouse gas) were higher for DME operation than for diesel operation. However, typical diesel engines operating on diesel fuel produce very low methane emissions. Therefore, although methane emissions increased by a factor of 24.18 for operation on DME as compared to diesel fuel, methane emissions on DME were still very low. Methane emissions could be further reduced by optimization of the fuel injection and combustion systems.

Ethylene and propylene emissions were reduced to insignificant levels for operation on DME. Combined ethylene and propylene emissions (ground level ozone components) for diesel operation were significant.

It is anticipated that further significant reductions in exhaust emissions can be realized by optimizing the DME injection/combustion systems, incorporating an EGR system and installing a more effective exhaust catalyst. It is recommended that follow-on work as outlined in Section 5 be performed to further reduce the DME exhaust emissions.

With regard to vehicle operation on DME, there is a need to incorporate additional fuel handling/supply safety precautions to minimize the potential for fire or explosion. DME is significantly more flammable (lower flashpoint temperature and lower auto-ignition temperature) and volatile than diesel fuel. DME fuel system components such as valves, lines and fittings should be constructed from non-sparking metals such as stainless steel or brass to minimize the possibility of generating a spark, which might lead to a fire situation. In addition, it would be necessary to ground the DME fuel tank and fuel lines to prevent electrostatic charge buildup and a potential spark discharge.

Components that cannot be replaced with stainless steel or brass should be constructed from Teflon or Butyl-N rubber, which are chemically resistant to DME and the traces of methanol typically found in commercial in DME. Fire-safe ball valves with graph-oil packing are

recommended for use as emergency DME shut-off valves. The graph-oil packing provides high temperature capabilities and resistance to temperature cycling, allowing the valve to seal even during a fire situation.

Based on the vehicle fuel system design, efforts were made to determine if the injector nozzles would leak DME from the high-pressure fuel line upon engine shutdown. Significant modifications were made to the mass leak rate measuring system to allow minute rates of DME leakage to be detected. Efforts were also made to allow more accurate thermal cycling of the injectors. DME leak rate tests carried out on new unused injection nozzle indicated no measurable leakage of DME at pressures up to 600 psi (room temperature conditions) and temperatures up to 550°F (150 psi). Leak rate testing using worn injection nozzles (90 percent of the expected useful lifetime) also indicated no measurable leakage of DME. It is anticipated that DME leakage past the injection nozzles into the cylinders of an engine would be insignificant, such that difficulties associated with DME vapour in the cylinders at shutdown would not be encountered.

5. RECOMMENDATIONS FOR FOLLOW-ON WORK

DME appears to be a promising alternative to diesel fuel for CI engine operation with regard to meeting future exhaust emissions regulations. Significant reductions in many regulated and unregulated exhaust emissions were observed for DME operation without performing additional engine modifications directed at lowering emissions. It is anticipated that further reductions in NO_x, THC (as unburned DME), formaldehyde and methane emissions could be obtained.

It is recommended that the following tasks be performed to reduce the aforementioned emissions.

Tasks

1) Re-assemble the DME fuel system for the 5.9-litre Cummins engine and install the engine on the EC dynamometer in preparation for further emissions testing.

2) Install a PC-based weigh scale and associated components to allow fuel consumption rates to be determined.

3) Modify the DME injection timing to reduce NO_x emissions.

4) Modify the intake/exhaust system to incorporate EGR for NO_x reduction purposes.

5) Acquire information on various types of exhaust catalysts to determine whether there is potential to reduce NO_x, unburned DME and toxic non-regulated emissions using a specialized catalyst for DME operation.

6) Investigate the potential for reducing methane emissions.

7) Perform additional DME emissions testing implementing information and hardware arising from Tasks 1 to 5.

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[1] Christensen, R., Sorenson S. C., Jensen M. G., and Hansen, K. F. *Engine Operation on Dimethyl Ether in a Naturally Aspirated, DI Diesel Engine*, SAE Paper 971665, 1997.

[2] J.E. Sinor Consultants Inc., *Dimethyl Ether as a Transportation Fuel, A State-of-the-Art Survey*, Report prepared for the National Renewable Energy Laboratory, May 1997.

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[4] Ofner, H., Gill, D. W., and Krotscheck, C., *Dimethyl Ether as Fuel for CI Engines - A New Technology and its Environmental Potential*, SAE Paper 981158, 1998.

[5] Advanced Engine Technology Ltd., *A Study of Dimethyl Ether (DME) as an Alternative Fuel for Diesel Engine Applications Phase I*, Report prepared for Alternative Energy Division, Natural Resources Canada, May 1996.

[6] Advanced Engine Technology Ltd., *Safety Considerations of Dimethyl Ether (DME) as an Alternative Diesel Fuel*, Report prepared for Transportation Development Centre, Transport Canada, TP 13456E, October 1999.

[7] Advanced Engine Technology Ltd., *Technical Focus on DME Fuel System Safety and Fuel Injection System Guidelines*, Meeting Report on the 3rd International Energy Agency (IEA) Workshop on Dimethyl Ether (DME), February 1998.

Appendix A

Comparison of Physical and Chemical Properties for DME, Propane and Diesel Fuel

Comparison of Physical and Chemical Properties for DME, Propane and Diesel Fuel

Properties	DME (l)	Propane (l)	Diesel
Chemical Formula	CH_3OCH_3	C_3H_8	$C_nH_{1.8n}$
Molecular Weight	46	44	>100
Lower Heating Value - kJ/kg	28,800	46,400	42,500
Liquid Density - gm/ml @ 15°C	0.668	0.509	0.84
Boiling Point - °C	-24.9	-42.17	180 to 350
Viscosity - kg/m.s @ 25°C	~0.13	~0.2	2.0 to 4.0
Vapour Pressure - bar @ 25°C	5.1	9.4	
Bulk Modulus of Elasticity - Pa @ 25°C & 20 bar	$0.05x10^{10}$		$0.2x10^{10}$
Cetane Number	~70	~20	40 to 50
Relative Density of Gaseous Fuel vs. Air	Heavier	Heavier	Heavier

Appendix B

Photographic Documentation of AET Research Engine/DME Apparatus

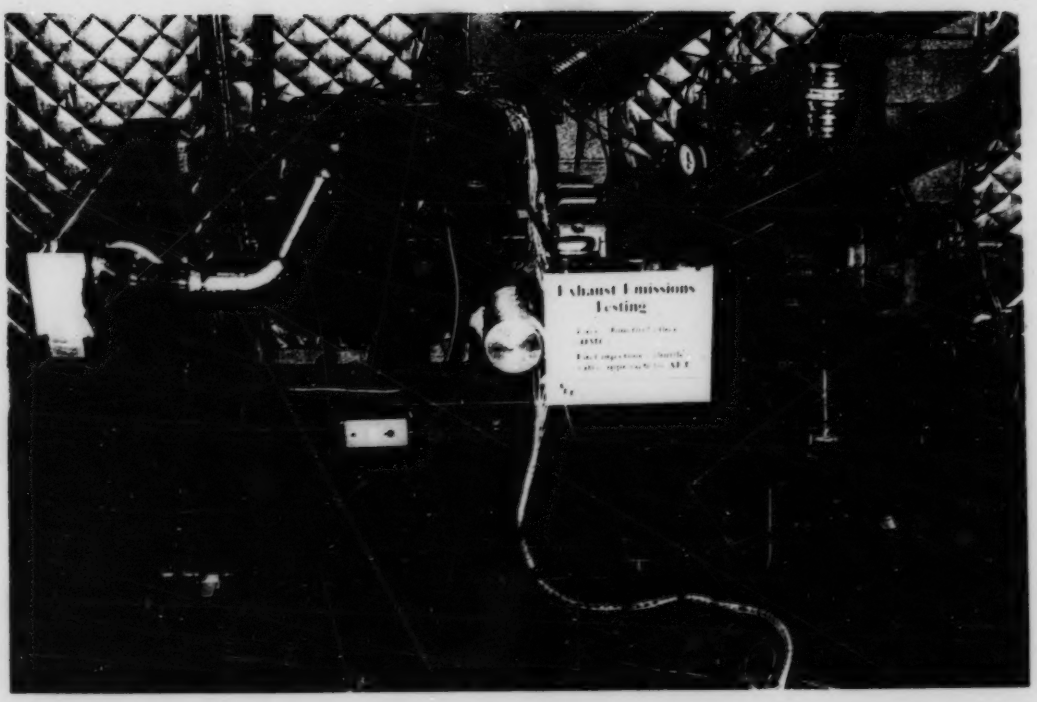


Figure B-1
5.9 L Cummins Diesel Engine and Waterbrake Dynamometer at EC

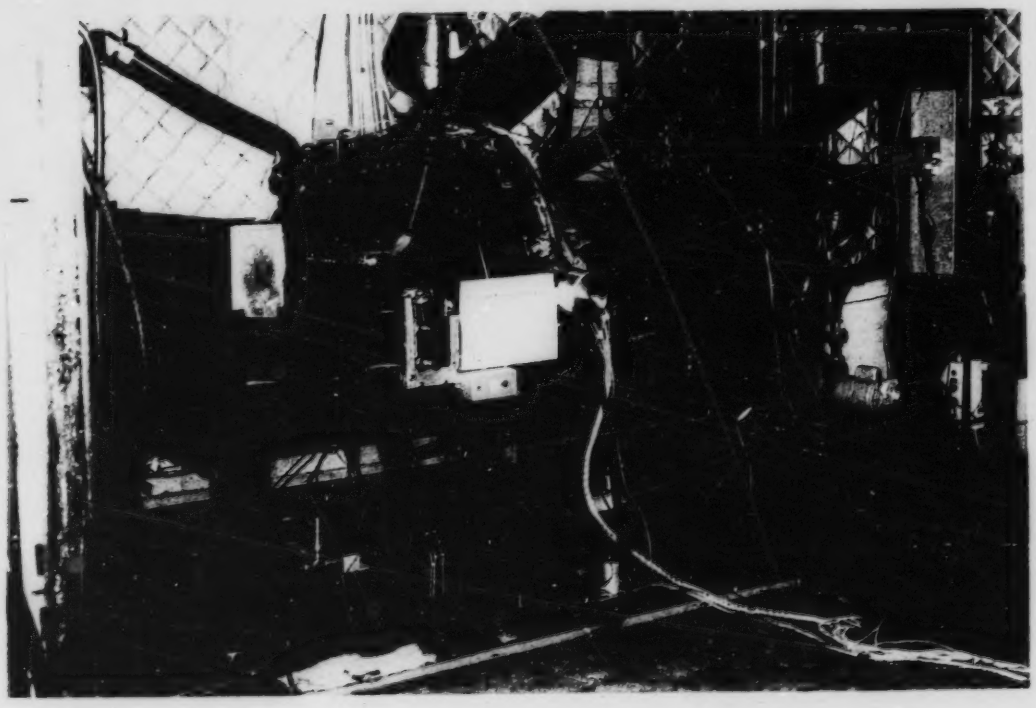


Figure B-2
5.9 L Cummins Diesel Engine and Waterbrake Dynamometer at EC

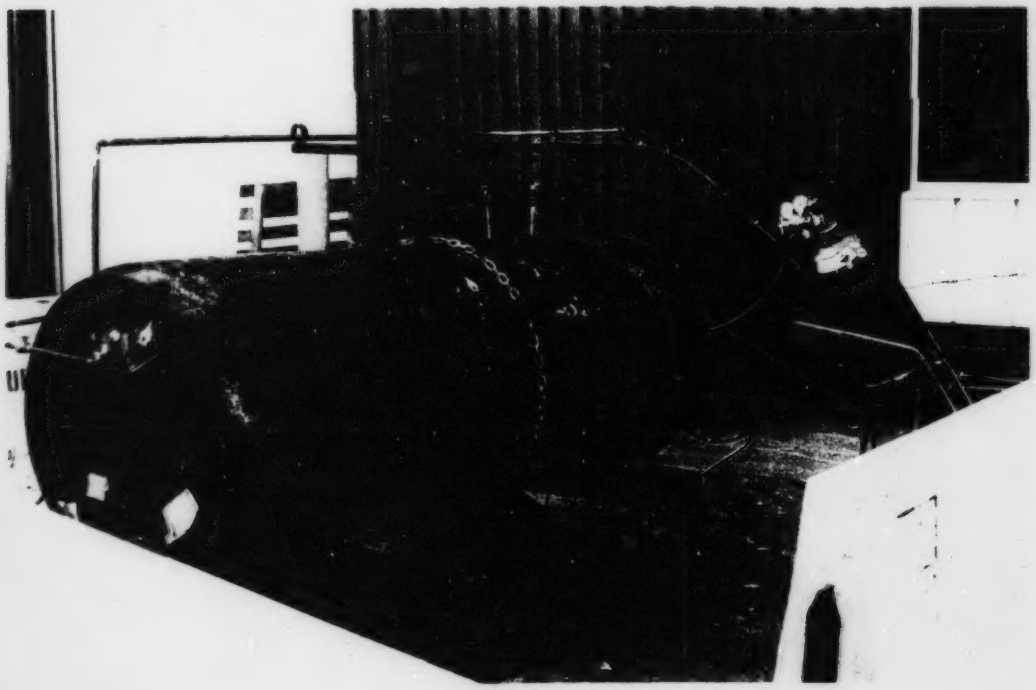


Figure B-3
2000 lb. High Pressure Reservoir for DME Storage at EC

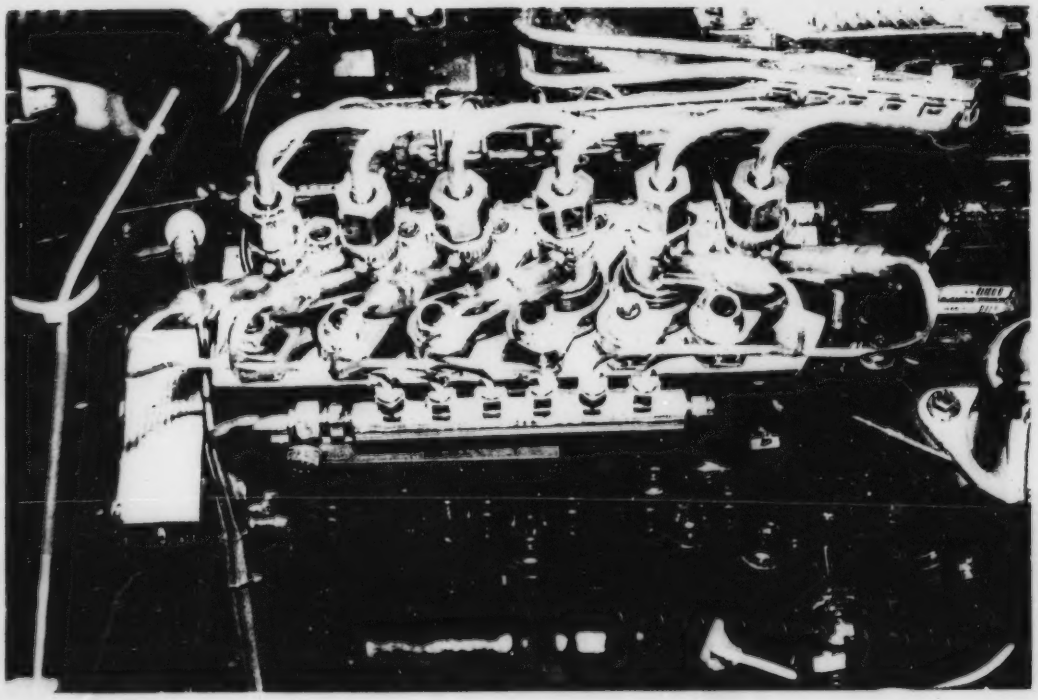


Figure B-4
AET DME Fuel Injection System Shuttle/Check Valve Installed on the Bosch Fuel Injection Pum

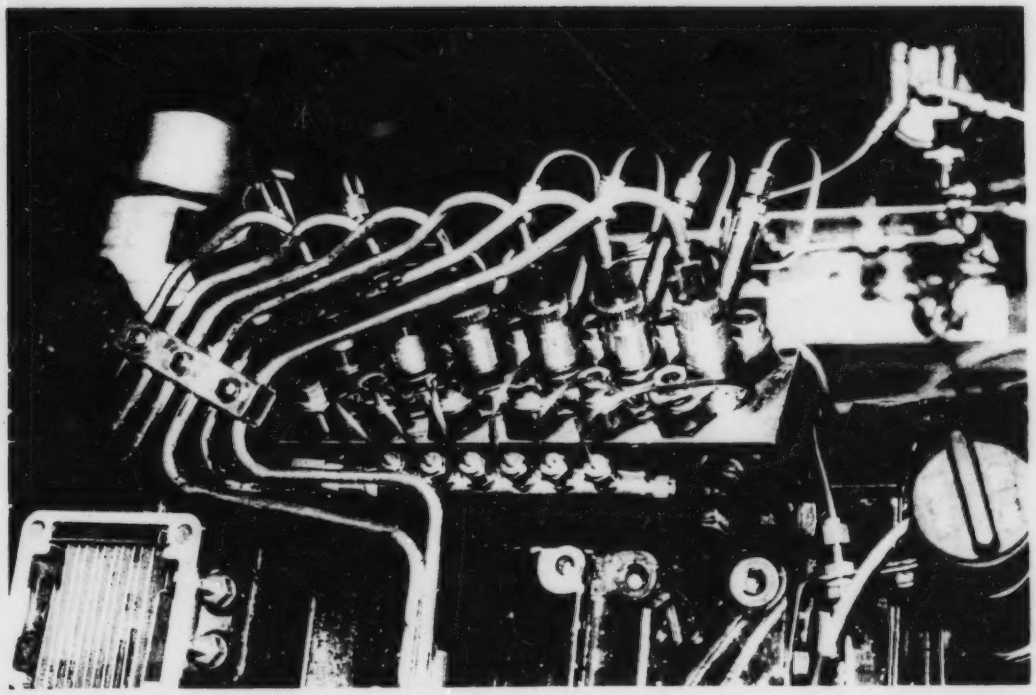


Figure B-5
AET DME Fuel Injection System Shuttle/Check Valve Installed on the Bosch Fuel Injection Pump

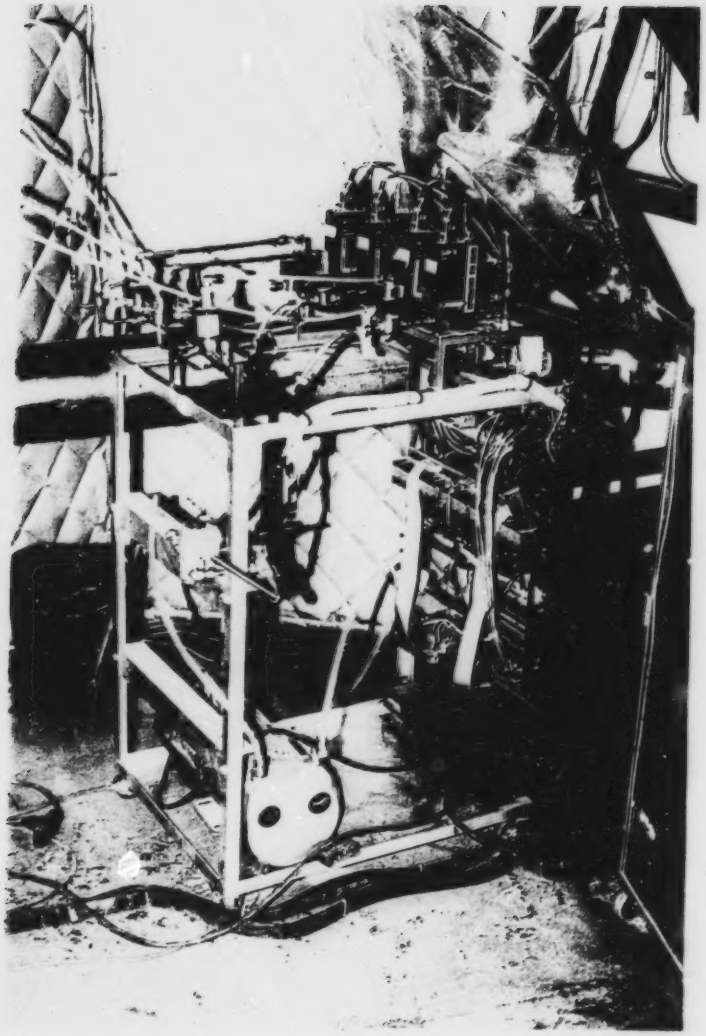


Figure B-6
Emissions Test Apparatus at EC

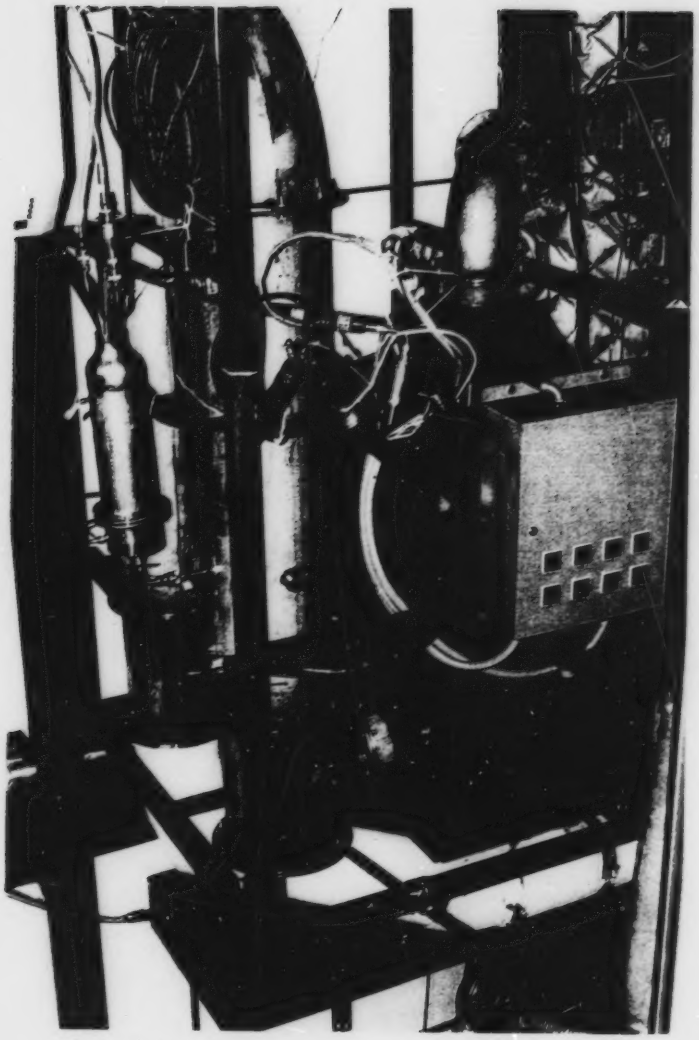


Figure B-7
Emissions Test Apparatus at EC

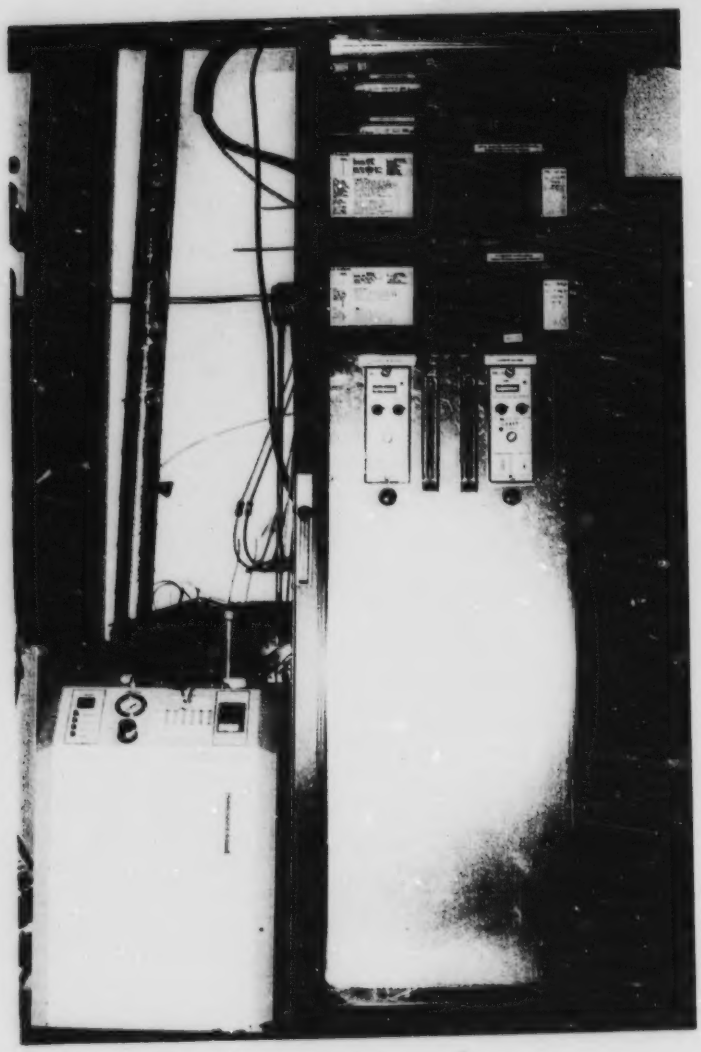


Figure B-8
Emissions Test Apparatus at EC

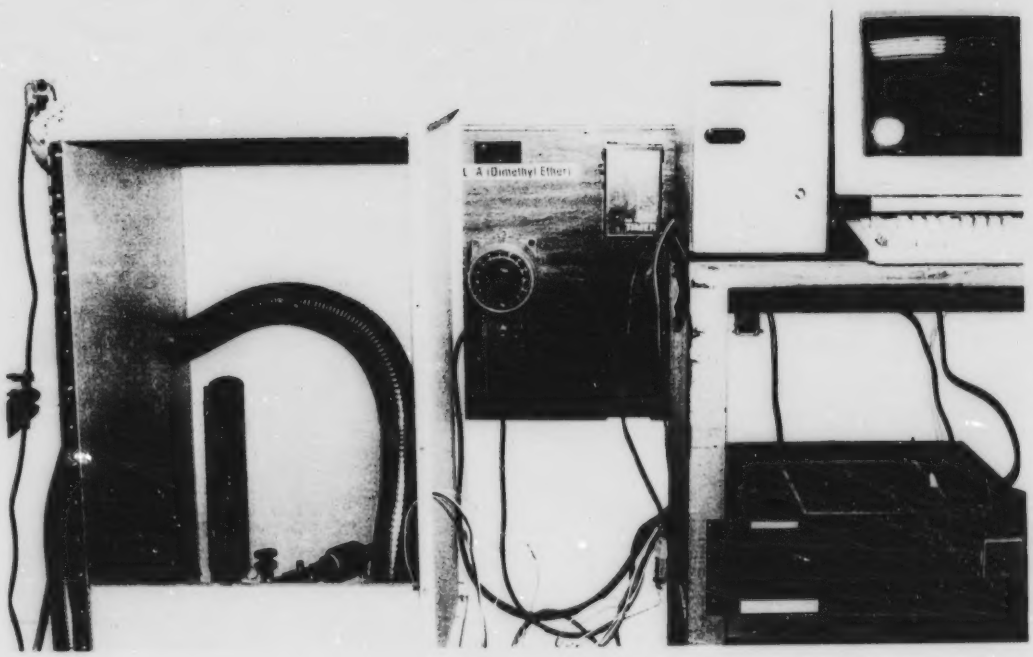


Figure B-9
Overall View of DME Leak Test Rig Showing Pressure Vessel, Insulative Wrap Surrounding Thermostatically Controlled Heating Element and Injector Nozzle, PC, PC Data Acquisition System and Injector Nozzle Temperature Control System

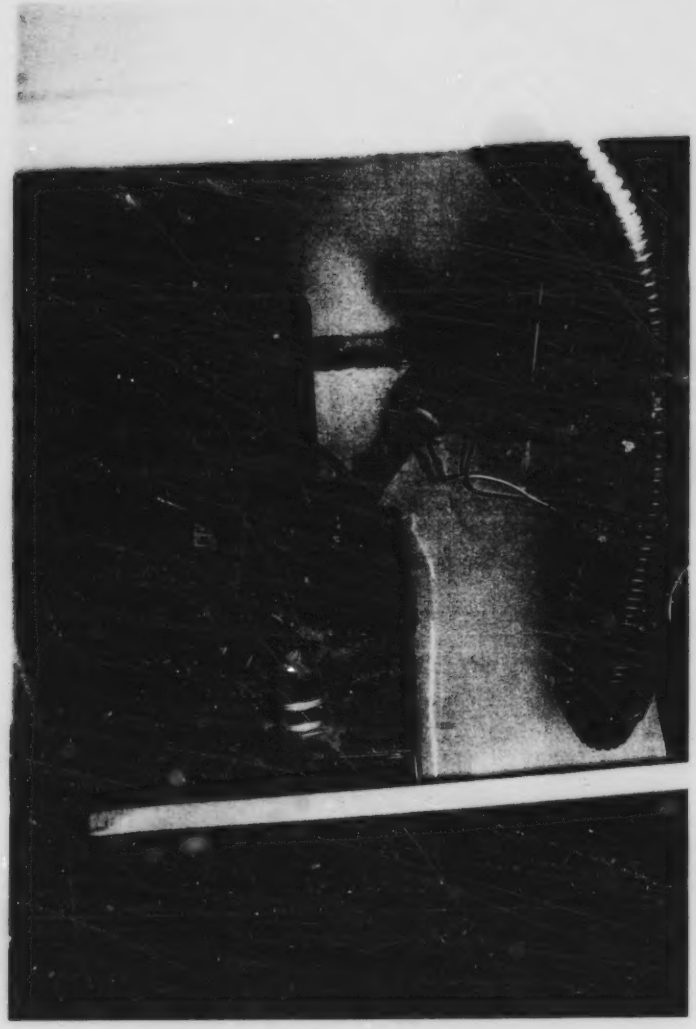
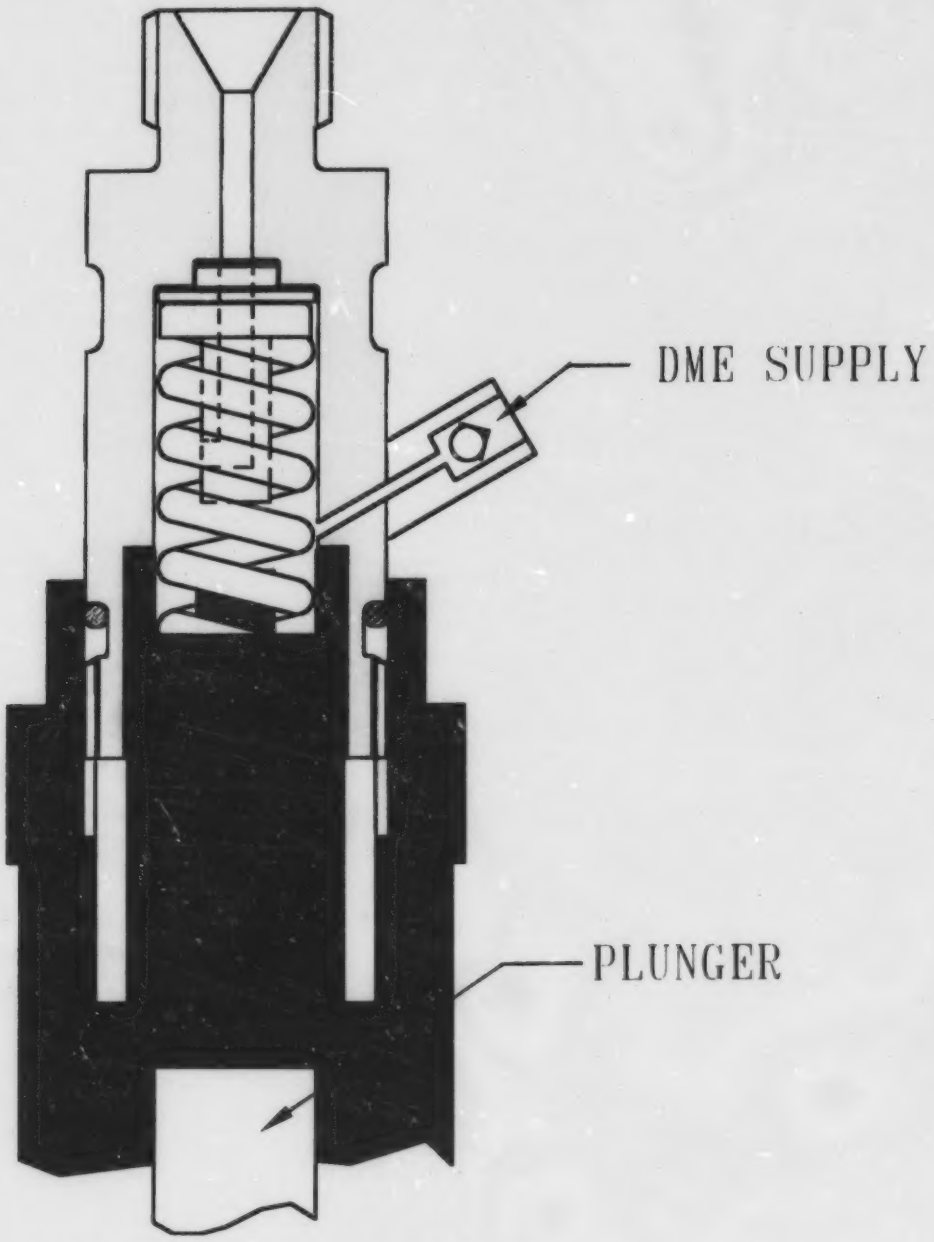


Figure B-10
Close-up View of DME Leak Test Rig Showing Pressure Vessel, Pressure Gauge, Shutoff Valve, Insulative Wrap Surrounding Thermostatically Controlled Heating Element and Injector Nozzle, PC Weigh Scale and Injector Nozzle Temperature Measurement

Appendix C

AET DME/Diesel Fuel Shuttle Valve

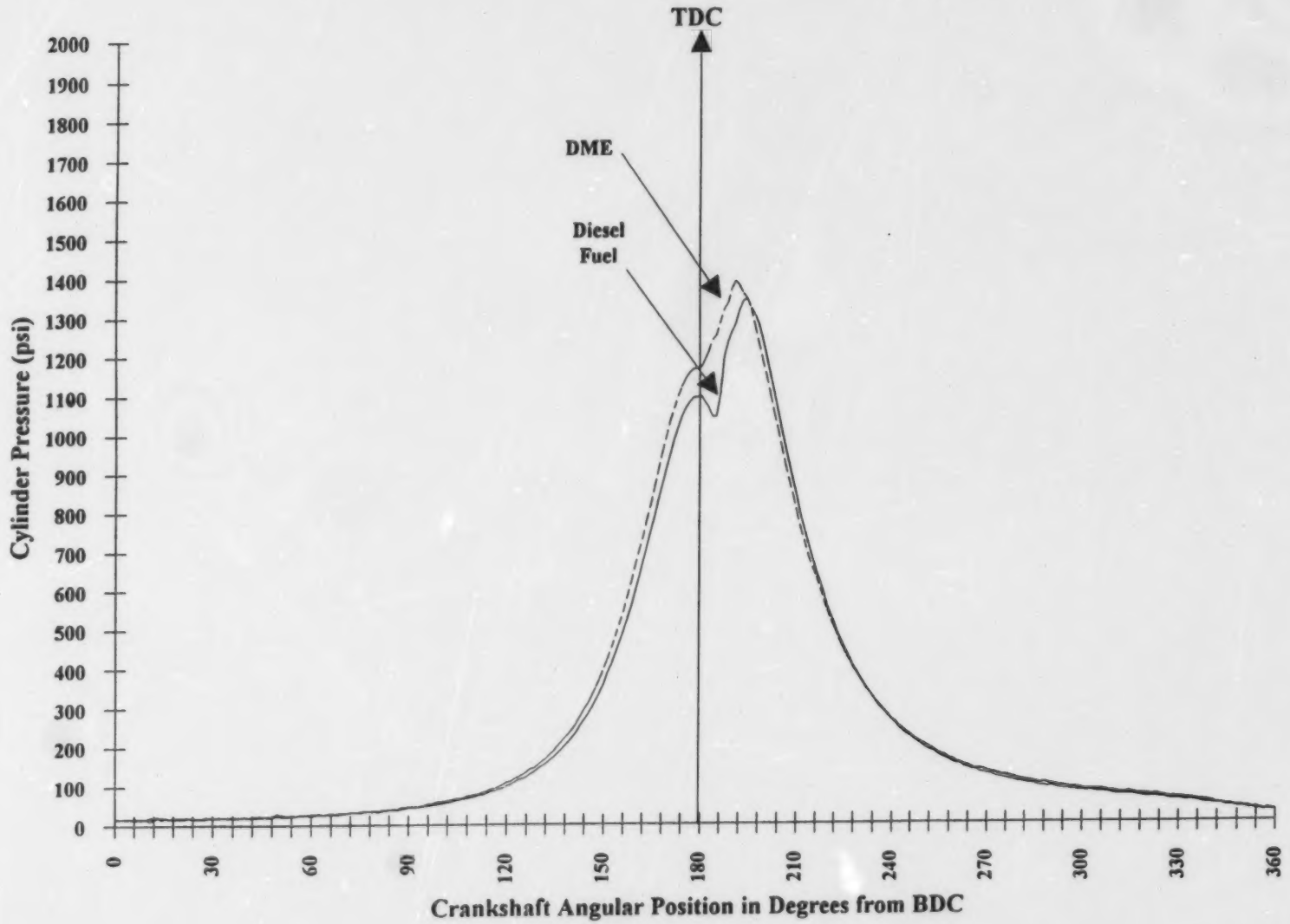


TRANSFER VALVE

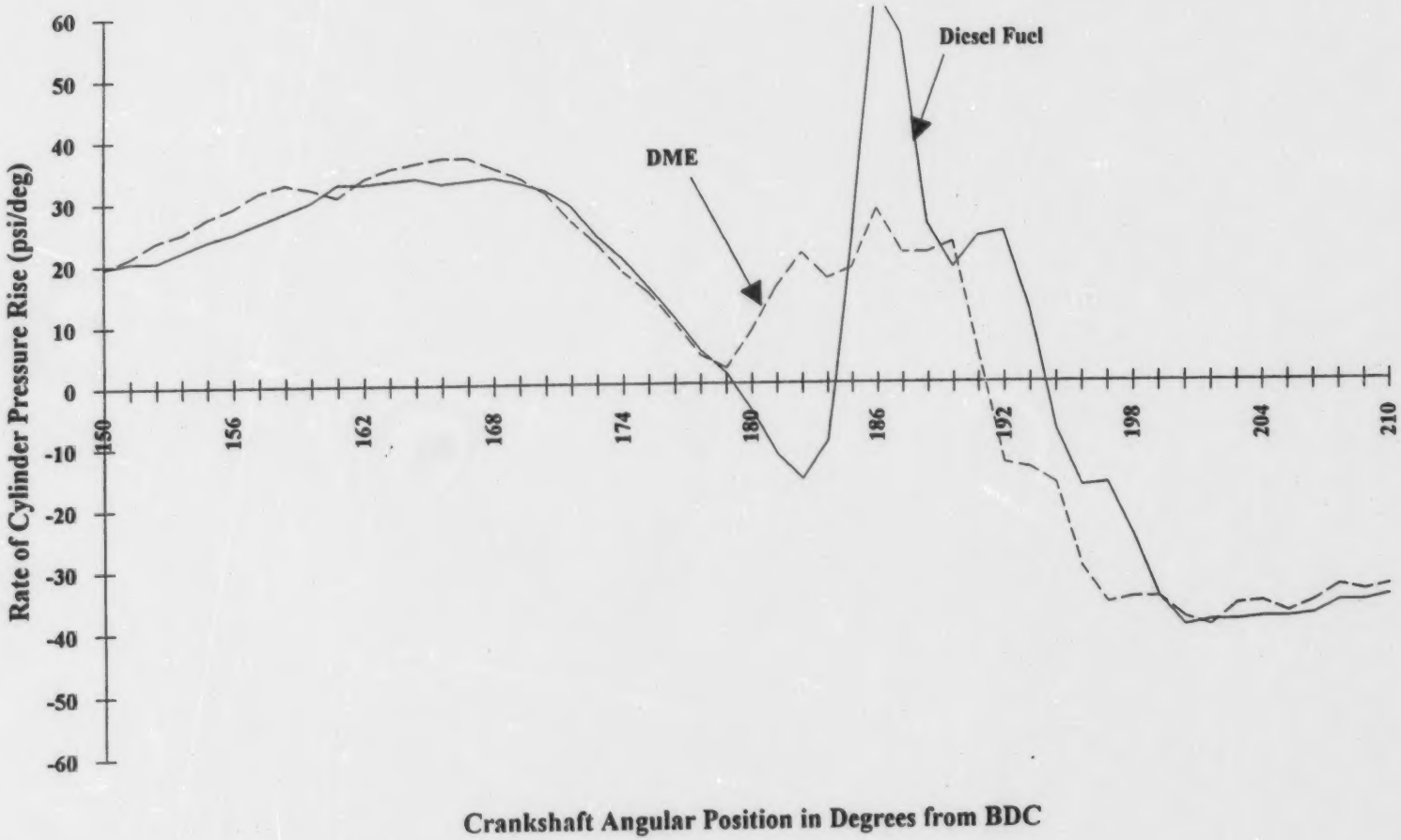
BARREL CLAMP TOWER
BOSCH PUMP BARREL
INJECTOR PUMP BARREL
SHUTTLE VALVE
DIESEL FUEL

Appendix D

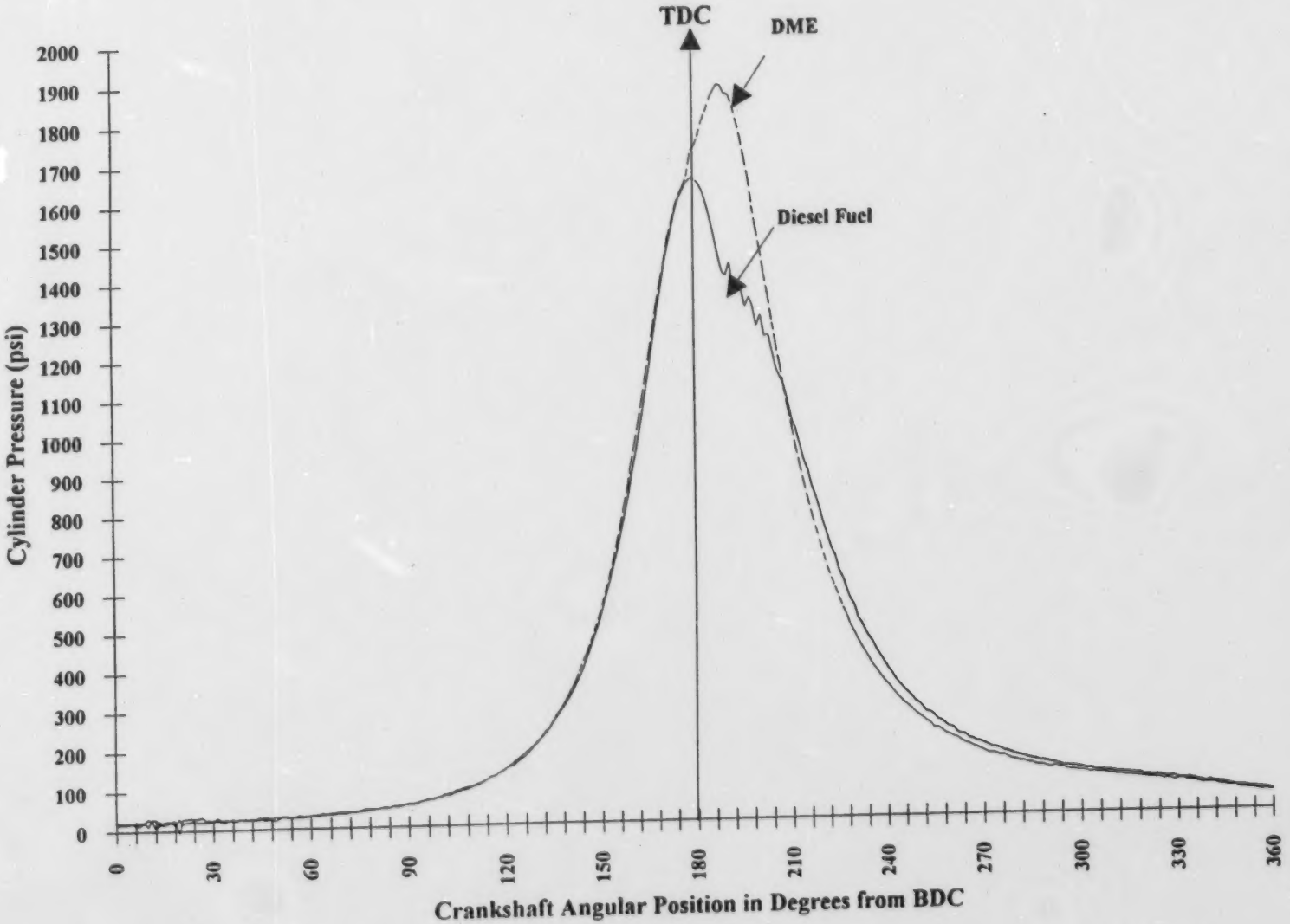
Comparison of Cylinder Pressure and Rates of Cylinder Pressure Rise for DME and Diesel Operation


Cylinder Pressure vs. Crankshaft Angular Position (Mode 4)
TDC
DME
Diesel Fuel
Cylinder Pressure (psi)
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
30
60
90
120
150
180
210
240
270
300
330
360
Crankshaft Angular Position in Degrees from BDC

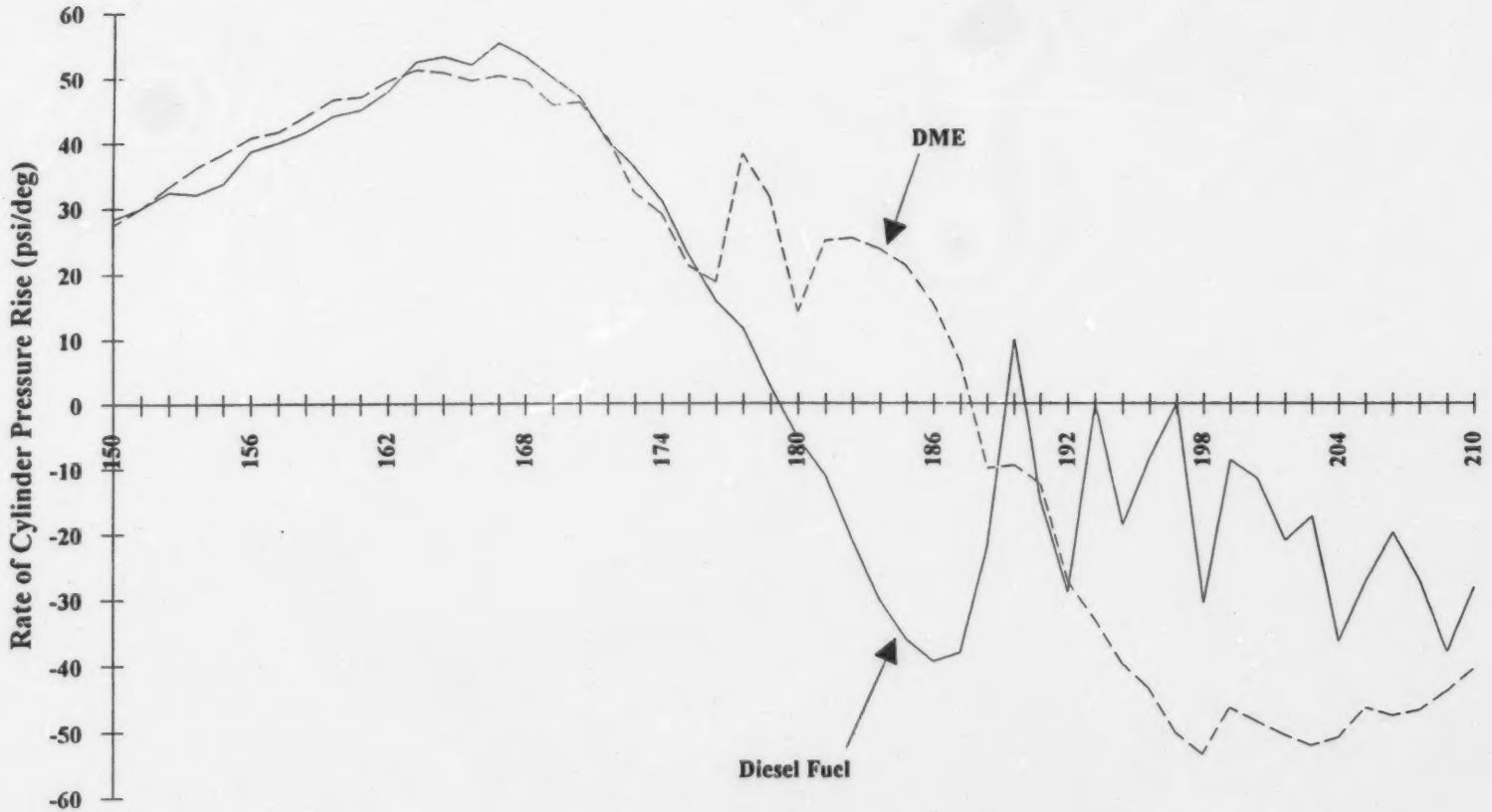
Rate of Cylinder Pressure Rise vs. Crankshaft Angular Position (Mode 4)



Cylinder Pressure vs. Crankshaft Angular Position (Mode 8)



Rate of Cylinder Pressure Rise vs. Crankshaft Angular Position (Mode 8)



Appendix E

AVL 8 Mode Emissions Test Engine Load and Speed Specifications

AVL 8 Mode Emissions Test Engine Load and Speed Specifications

Mode	Engine Speed (RPM)	Load (bhp)	Weighting Factor (%)
1	850	0	35
2	1031	17	6.34
3	1163	56	2.91
4	1378	93	3.34
5	2500	62	8.4
6	2417	71	10.45
7	2417	122	10.21
8	2318	165	7.34

Note - The actual engine load (62 bhp) for Mode 5 was approximately twice the desired load value (32 bhp) because of difficulties with the EC dynamometer maintaining very light loads at high engine speeds.

Appendix F

Failure Mode and Effect Analysis (FMEA) of a Dimethylether (DME) Fuel System for Light-Duty Vehicle Applications

ADVANCED ENGINE TECHNOLOGY Ltd.
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FAILURE MODE AND EFFECT ANALYSIS (FMEA) OF A DIMETHYLETHER (DME) FUEL SYSTEM FOR LIGHT DUTY VEHICLE APPLICATIONS

Submitted to
Participants of
IEA/AMF Annex 14 - R&D Task 3
International DME FMEA Assessment Conference
October 1 & 2, 1998
Delft, Netherlands

by

Advanced Engine Technology Ltd.

BUSINESS CONFIDENTIAL

October 1998
Nepean, Ontario

Phone: (613) 721-1234

Table of Contents

DME Fuel Injection System Boundary Conditions - Flow Chart F-3

DME Fuel System for Light Duty Vehicle Applications - CAD Drawing F-4

Engine/Fuel System State Summary F-5

Summary of Implicit Assumptions F-6

Summary of Modifications Made to the AET - DME Engine/Vehicle Fuel System Based on the Risk Assessment from the first FMEA Evaluation F-7

1.0 FMEA Evaluation - DME Fuel Supply System F-9

2.0 FMEA Evaluation - Diesel Fuel Supply System F-10

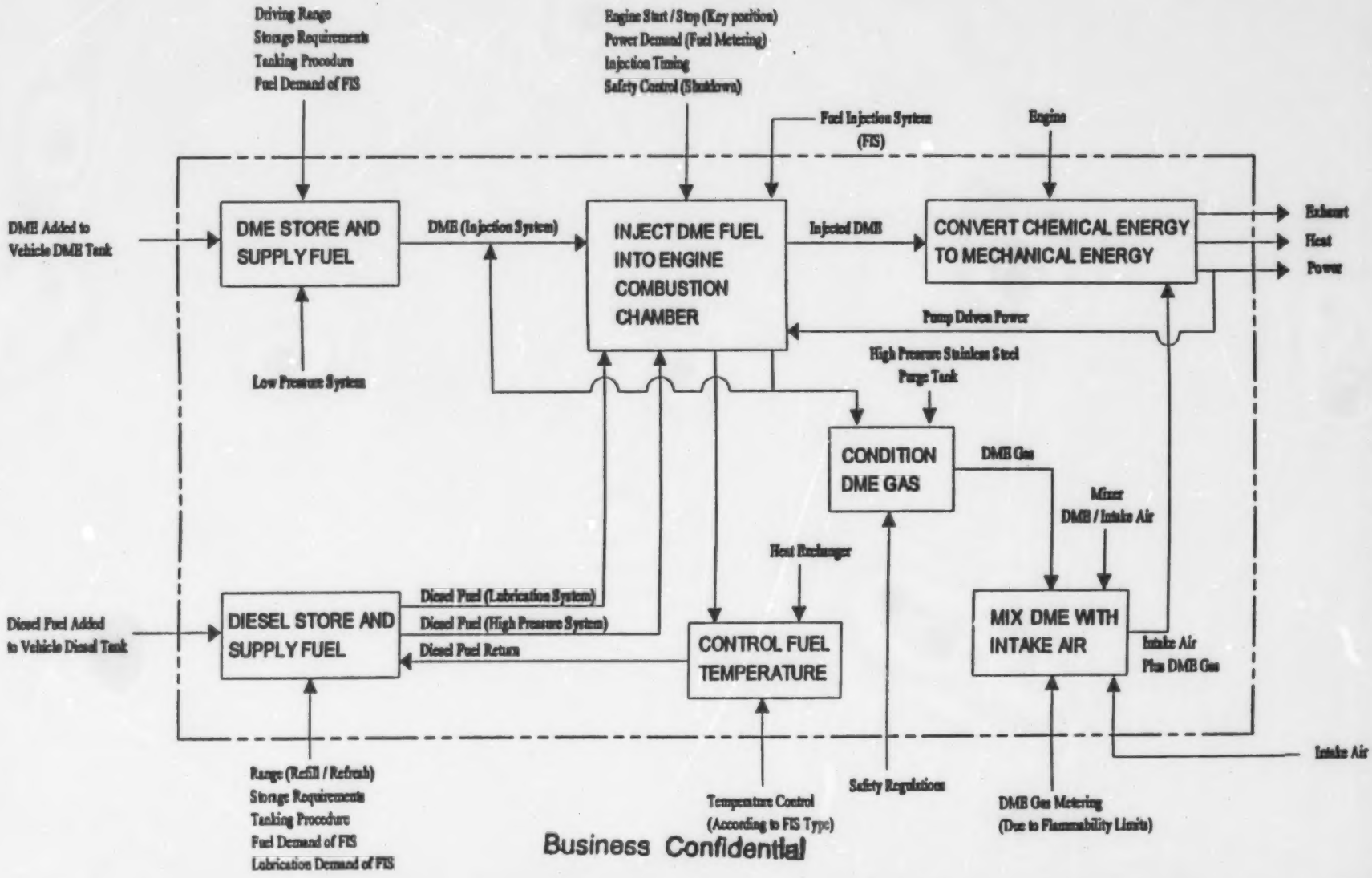
3.0 FMEA Evaluation - Fuel Injection System F-11

4.0 FMEA Evaluation - DME Fuel Return System F-13

5.0 FMEA Evaluation - DME Fuel Control System F-14

6.0 FMEA Evaluation - Diesel Fuel Control System F-16

FUEL INJECTION SYSTEM BOUNDARY CONDITIONS



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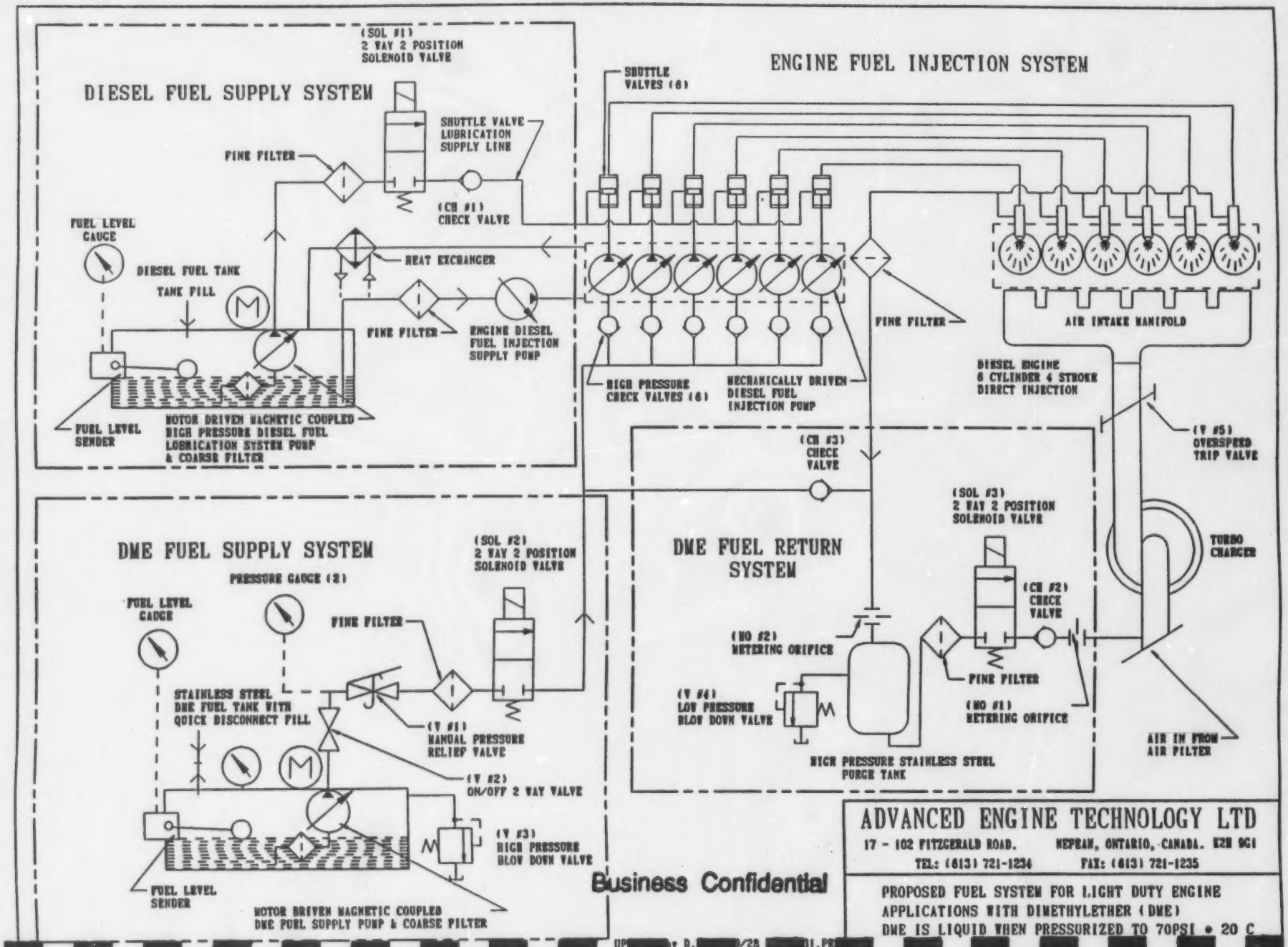
(SOL #1)
2 WAY 2 POSITION
SOLENOID VALVE
DIESEL FUEL SUPPLY SYSTEM
SHUTTLE VALVE
LUBRICATION
SUPPLY LINE
FINE FILTER
(CH #1)
CHECK VALVE
FUEL LEVEL
GAUGE
HEAT EXCHANGER
DIESEL FUEL TANK
TANK FILL
FINE FILTER
ENGINE DIESEL
FUEL INJECTION
SUPPLY PUMP
FUEL LEVEL
SENDER
MOTOR DRIVEN MAGNETIC COUPLED
HIGH PRESSURE DIESEL FUEL
LUBRICATION SYSTEM PUMP
& COARSE FILTER
ENGINE FUEL INJECTION SYSTEM
SHUTTLE
VALVES (6)
FINE FILTER
AIR INTAKE MANIFOLD
DIESEL ENGINE
6 CYLINDER 4 STROKE
DIRECT INJECTION
HIGH PRESSURE
CHECK VALVES (6)
MECHANICALLY DRIVEN
DIESEL FUEL
INJECTION PUMP
(V #5)
OVERSPEED
TRIP VALVE
(CH #3)
CHECK
VALVE
(SOL #3)
2 WAY 2 POSITION
SOLENOID VALVE
TURBO
CHARGER
DME FUEL SUPPLY SYSTEM
(SOL #2)
2 WAY 2 POSITION
SOLENOID VALVE
PRESSURE GAUGE (2)
FUEL LEVEL
GAUGE
FINE FILTER
DME FUEL RETURN
SYSTEM
(CH #2)
CHECK
VALVE
(NO #2)
METERING ORIFICE
FINE FILTER
STAINLESS STEEL
DME FUEL TANK WITH
QUICK DISCONNECT FILL
(V #4)
LOW PRESSURE
BLOW DOWN VALVE
(NO #1)
METERING ORIFICE
(V #1)
MANUAL PRESSURE
RELIEF VALVE
(V #2)
ON/OFF 2 WAY VALVE
HIGH PRESSURE STAINLESS STEEL
PURGE TANK
AIR IN FROM
AIR FILTER
(V #3)
HIGH PRESSURE
BLOW DOWN VALVE
FUEL LEVEL
SENDER
MOTOR DRIVEN MAGNETIC COUPLED
DME FUEL SUPPLY PUMP & COARSE FILTER
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ADVANCED ENGINE TECHNOLOGY LTD
17 - 102 FITZGERALD ROAD. NEPEAN, ONTARIO, CANADA. K2R 9G1
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PROPOSED FUEL SYSTEM FOR LIGHT DUTY ENGINE
APPLICATIONS WITH DIMETHYLETHER (DME)
DME IS LIQUID WHEN PRESSURIZED TO 70PSI • 20 C

Engine/Fuel System State Summary

State	Key	SOL#1	SOL#2	SOL#3	DME Fuel Supply Pump	Diesel Fuel Injection Supply Pump	Diesel Fuel Lubrication System Pump	Starter Motor
Engine off	Off	Off	Off	Off	Off	Off	Off	Off
Ready for startup	On	On	On	Off	On	Off	Off	Off
Cranking engine	Start	On	On	Off	On	On	On	On
Engine operation	On	On	On	On	On	On	On	Off
Engine shutdown	Off	Off	Off	Off	Off	Off	Off	Off

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Summary of Implicit Assumptions

1) All fittings selected for the vehicle fuel system do not leak.

2) All fuel system components are of single walled construction.

3) The high DME pressures in the high pressure fuel injection lines are bled off upon engine shutdown.

4) A purge tank is used to collect DME from the high pressure fuel injection lines upon engine shutdown. The purge tank allows the DME liquid in the high pressure fuel injection lines to gasify to a low pressure upon engine shutdown, thereby preventing DME from leaking through the injection nozzle needle/seat into the engine's combustion chamber. The purge tank is sized to absorb substantially more DME than the DME quantity in the high pressure fuel injection lines.

5) Blow down valves are used to vent the DME to atmosphere in a controlled manner if a malfunction in the fuel system or emergency situation causes excessive DME pressures. The low pressure blow down valve (V#4) and high pressure blow down valve (V#3) are in the closed positions during normal functioning of the vehicle fuel system. However, during a condition of excessive DME pressure the appropriate valve will open to vent the DME to atmosphere. The valves are located at an elevated level near the rear of the vehicle to minimize any fire hazards. During a fire the valves would vent the DME in a controlled manner minimizing the possibility of an explosion.

6) The engine has an overspeed trip valve (V#5) to limit the engine speed in the event that a malfunction causes DME to enter the intake air system in significant quantities prior to engine startup. Significant quantities of DME in the intake air system upon engine startup can result in severe engine overspeeding since the neither the quantity of air or fuel entering the engine's cylinders is regulated until the DME in the intake air system is consumed. An engine overspeed trip valve (V#5) is used to limit engine speed in the event that a malfunction causes DME to enter the intake air system in significant quantities prior to engine startup.

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Summary of Modifications Made to the AET - DME Vehicle/Engine Fuel System Based on the Risk Assessment from the First FMEA Evaluation

Based on the FMEA evaluation it was concluded that difficulties would arise during operation of the AET-DME engine system due to the significant rate of DME return flow from the injection nozzles. The DME return flowrate would be greater than the allowable DME flowrate into the engine induction system, especially under idling conditions, thereby leading to combustion of the inducted DME, engine knock and engine overspeeding (limited by the overspeed trip valve). Efforts have been made to eliminate this difficulty without creating other difficulties, such as increased potential for DME to leak through the injection nozzles into the engines' cylinders during shutdown.

It was concluded that the FMEA risk assessment for the AET-DME engine system could be improved by : 1) modifying the DME return system to vent primarily from the injection nozzle returns to the low pressure DME fuel supply line with only a small percentage of the return DME being directed to the engine induction system, 2) replacing the charcoal canister with a stainless steel purge tank. The DME injection nozzle return lines would be connected directly to the low pressure DME supply line, employing a check valve to control the DME flow direction. The DME injection nozzle return lines would also be connected directly to the purge tank, employing an orifice to restrict the DME flow into the purge tank. It is anticipated that a stainless steel purge tank would be more compatible with DME contaminants such as diesel fuel and methanol than a charcoal filled canister.

During engine operation DME would exit the injection nozzle returns and enter the purge tank at a low flowrate as dictated by the metering orifice (MO#2). DME would then flow through the purge tank, fine filter, solenoid valve (SOL#3), check valve (CH#2), metering orifice (MO#1) and into the engine induction system. The flow restriction generated by metering orifice (MO#2) would cause the pressure in the DME return line between the injection nozzles and orifice to increase, eventually causing the check valve (CH#3) to open allowing most of the DME return flow to enter the low pressure DME supply line. The DME return line pressure would then stabilize just above the low pressure DME supply line pressure.

Very little of the DME return fuel would enter the engine through the induction system thereby minimizing the risks associated with combustion of the inducted fuel causing knock, excessive engine speeds and possibly engine damage. It is anticipated that metered orifice controls would be less likely to fail than solenoids and valves. It should be noted that both check valves (CH#2/CH#3) and both metering orifices (MO#1/MO#2) are protected from blockage by fine metal filters, further reducing the risk level.

Upon engine shutdown DME in the high pressure injection lines would be bled off into the return system. DME would pass from the injection nozzle returns into the purge tank through

the metered orifice (MO#2) reducing the pressure in the high pressure injection lines to a low level. The purge tank would be sized to allow for additional DME bleed-down if check valve (CH#3) failed to close upon shutdown.

Upon engine startup solenoid valve (SOL#3) would open allowing the low pressure DME in the purge tank to enter the induction system through metering orifice (MO#1) at a very low flowrate such that engine knock and overspeeding would not occur.

In conclusion it is anticipated that the addition of check valve (CH#3) and metering orifice (MO#3), in addition to replacing the charcoal canister with a stainless steel purge tank, would significantly reduce the FMEA risk assessment for the AET-DME engine system.

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation			
				O	I	D	RPN
1. DME fuel supply system							
1.1 DME fuel storage system (fuel tank, pump, pump motor, fuel level sender, gauges, filters)							
Fu. 1: Delivers liquid DME from the fuel tank to the engine fuel injection system when the engine is turned on (DME fuel pump=ON). DME pressure equals vapour pressure and fluctuates with ambient temperature conditions	Fuel delivery rate too low /supply pressure too low	DME pressure in injection system drops causing partial vaporization of DME, erratic engine operation, engine shutdown	Hydraulic failure of supply pump (valves, plungers,diaphragms, seals etc.)				
			Supply pump motor failure				
			Drive failure between motor and pump				
			Supply line and/or filters blocked				
			Fuel tank empty due to malfunction of pressure gauge, fuel level sender, or fuel level gauge				
Fu. 2. Stops fuel delivery when the engine is shutdown (DME fuel supply pump=OFF).	Fuel delivery during engine shutdown	No effects on system if on/off 2 way valve (V#2) is closed, or solenoid valve (SOL#2) is closed. Else DME passes into injection system, return system, fills purge tank and may exit through low pressure blow down valve (V#4)	Mechanical or electrical failure between ignition key and DME fuel supply pump motor				

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System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation			
				O	I	D	RPN
2. Diesel fuel supply system							
2.1 Diesel fuel storage system (fuel tank, pumps, pump motor, fuel level sender, gauges, filters)							
Fu. 1: Delivers diesel fuel from the fuel tank to the engine fuel injection system when the engine is turned on (Diesel fuel supply pump=ON)	Fuel delivery rate too low /supply pressure too low/fuel aeration	Insufficient diesel fuel drawn into injection pump causing reduced shuttle valve displacement, erratic engine operation, engine shutdown	Mechanical/hydraulic failure of diesel engine fuel injection supply pump (valves, plungers,diaphragms, seals etc.)				
			Supply line and/or filters blocked				
			Fuel tank empty due to malfunction of pressure gauge, fuel level sender, or fuel level gauge				
			Air leak in diesel fuel supply line or pump				
Fu. 2: Delivers diesel fuel from the fuel tank to the shuttle valves for lubrication when the engine is turned on (Diesel fuel lubrication system pump=ON)	Fuel delivery rate too low /supply pressure too low/fuel aeration	Reduced shuttle valve lubrication resulting in increased shuttle valve wear and potential seizure	Mechanical/hydraulic failure of diesel fuel lubrication system pump (valves, plungers,diaphragms, seals etc.)				
			Diesel fuel lubrication system pump motor failure				
			Drive failure between motor and pump				
			Diesel fuel lubrication system supply line and/or filters blocked				
			Fuel tank empty due to malfunction of pressure gauge, fuel level sender, or fuel level gauge				
			Air leak in diesel fuel lubrication system line or pump				
Fu. 3: Stops fuel delivery to the engine fuel injection pump when the engine is shutdown (Diesel fuel supply pump=OFF).	Fuel delivery during engine shutdown not possible since the pump is mechanically driven by the engine	NA	NA				
Fu. 4: Stops diesel fuel delivery to the shuttle valves when the engine is shutdown (Diesel fuel lubrication system pump=OFF).	Fuel delivery during engine shutdown	No effects on system if solenoid valve (SOL#1) is closed. Else slow migration of diesel fuel from shuttle valve into the DME high pressure injection line causing engine startup on a mixture of diesel fuel and DME	Mechanical or electrical failure between ignition key and diesel fuel lubrication system pump motor				

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System/Item Component Function	Potential failure	Effect of failure	Cause of failure	Evaluation			
				O	I	D	RPN
3. Fuel injection system							
3.1 Diesel fuel injection pump							
Fu. 1: Supplies high pressure diesel fuel to activate shuttle valve system, corresponding to the required fuel injection period	Aeration of diesel fuel in the pump	Insufficient pressure generated during compression of diesel fuel to activate shuttle valve - resulting in erratic engine operation - engine may not start/operate	Insufficient diesel fuel supply in supply tank				
			Blockage of diesel fuel supply line/filtration system				
			Air leak in diesel fuel supply system allowing aeration of the diesel fuel				
	Seizure of plunger in barrel	Erratic engine operation - engine shutdown	Insufficient diesel fuel supply for pump barrel/plunger lubrication				
			Insufficient diesel fuel lubricity				
			Aeration of diesel fuel causing insufficient lubrication				
3.2 DME injection system high pressure check valves (6 units)							
Fu. 1: Valve opens at minimal pressure differential to allow DME from the DME supply line to enter the high pressure injection line	Check valve stays closed	DME does not transfer from the supply line into the high pressure injection line. Engine startup/operation cannot occur without DME transfer to one or more of the 6 high pressure injection lines	Blockage of DME supply line				
			Insufficient DME supply pressure				
			Seizure of check valves				
Fu. 2: Valve closes at minimal pressure differential preventing the injection pulse in the high pressure injection line from transferring into the DME supply line	Check valve leaks/stays open	High pressure line injection pulse weakened as a portion of the pulse enters the low pressure supply line - erratic engine operation/engine shutdown	Poor fuel lubricity causing excessive wear at the valve seat				
			Deposits on the check valve seat				
			Valve bouncing				
			Seizure of the check valve				

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System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation			
				O	I	D	R.P.N
3.3 Shuttle valve							
Fu. 1: Displacement of the shuttle valve causes a rapid buildup of pressure in the high pressure line corresponding to engine fuel injection timing requirements	Shuttle valve stays closed	No DME injection -the engine will not start/operate	Insufficient pressure buildup (diesel fuel) in diesel fuel injection pump				
	Shuttle valve stays open	No DME injection -the engine will not start/operate	Shuttle valve seizure from insufficient lubrication				
Fu. 2: Provides a sealed interface between the diesel fuel in the injection pump and the DME in the high pressure line	Shuttle valve leaks	Erratic fuel injection/engine operation	Insufficient lubrication provided by high pressure diesel fuel lubrication system				
			Deposits on valve seat				
			Valve seat wear				
			Excessive clearances between shuttle valve and barrel				
3.4 Fuel injection nozzle							
Fu. 1: Opens orifice to combustion chamber for fuel injection if pressure inside nozzle has exceeded Needle Opening Pressure (NOP)	Orifice stays closed	No fuel injection	Seizure of nozzle needle				
			Excessive pressure in nozzle spring chamber due to blocked return line				
Fu.2: Closes orifice to combustion chamber if pressure inside nozzle is below NOP	Orifice is open even if pressure in high pressure line is below NOP	Erratic fuel injection	Seizure of nozzle needle				
			Particles on needle seat				
			Leakage past needle due to poor fuel lubricity causing excessive wear				
			Needle bouncing				
			Excessive wear at needle/seat interface				

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System/Item Component Function	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN
4. DME fuel return system							
4.1 DME fuel return storage and regulation							
Fu. 1: Contain DME exiting from the injection nozzle returns, in a low pressure gaseous state, upon engine shutdown	Leakage of DME into engine induction system upon engine shutdown	DME gas in engine induction system may cause engine knock and/or momentary excessive engine speeds (limited by overspeed trip valve V#5) upon engine startup	Solenoid valve (SOL#3) does not close upon engine shutdown				
	Leakage of DME out of low pressure blow down valve (V#4) upon engine shutdown	Slow venting of DME into the atmosphere through low pressure blow down valve (V#4)	Malfunction of low pressure blow down valve				
			DME fuel supply pump remains on and/or solenoid valve (SOL#2) remains open upon engine shutdown causing a continuous migration of DME into the DME return system purge tank				
Fu. 2: Return the flow of DME exiting from the DME fuel injection nozzle returns into the low pressure DME line during engine operation	No flow of DME from the injection nozzle return lines into the low pressure DME supply line during engine operation	Increasing back-pressure in the injection nozzle return lines, eventually preventing the injection nozzle needles from lifting, resulting in engine shutdown	Sticking/seizure of check valve (CH#3)				
			Return line and/or metering orifice blockage				
Fu. 3: Return a metered quantity of DME exiting from the DME fuel injection nozzle returns into the engine air induction system during engine operation	Leakage of DME out of low pressure blowdown valve (V#4)	Slow venting of DME into atmosphere through low pressure blow down valve (V#4)	Solenoid valve (SOL#3) does not open upon engine startup				
			Sticking/seizure of check valve (CH#2)				
			Return line and/or metering orifice blockage				

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Subsystem Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation			
				O	S	D	RPN
5. DME fuel control system							
5.1 Solenoid valve (SOL#2) - 2 position/2 way valve							
Fu. 1: DME fuel supply shut off (valve not powered) - closed exit when engine is shut off	Solenoid exit remains partially or fully open	Continuous migration of DME into the DME return system purge tank eventually causing DME to vent through low pressure blow down valve (V#4)	Mechanical failure of valve				
			Valve powered due to an electrical malfunction				
Fu. 2. DME fuel supply turned on (valve powered) - open exit when engine is turned on	Solenoid exit remains in closed position	DME is not supplied to injection system as such the engine will not start	Mechanical failure of valve				
			Valve not powered due to electrical malfunction				
5.2 Manual pressure relief valve (V#1)							
Fu. 1: Valve is opened only in an emergency situation to vent the DME from the DME fuel supply system if the high pressure blow down valve (V#3) malfunctions	Valve left partially open when emergency venting of the DME storage tank is not required	Leakage of DME into the atmosphere (fuel supply tank may empty completely) - minimal leakage if ON/OFF 2 way valve is in closed position. The DME fuel supply pump may not develop enough pressure to allow engine startup/operation	Operator error				
5.3 ON/OFF 2 way valve (V#2)							
Fu. 1: Valve is closed only to shut off DME storage system from the supply line to allow venting of the supply line prior to performing supply line/injection system repairs	Valve is placed in closed position during engine startup /operation	Insufficient supply of DME to the injection pump causing erratic engine operation, engine shutdown	Operator error				
5.4 High pressure blow-down valve (V#3)							
Fu. 1: Protects DME fuel supply system components from excessive pressure	Excessive pressure due to high ambient temperatures or overfilling	Breakage of supply system components, DME leakdown	Malfunction of high pressure blow down valve				
5.5 Solenoid valve (SOL#3) - 2 position/2 way valve							
Fu. 1: DME fuel return to engine induction system shut off (valve not powered) - closed exit when engine is shut off	Solenoid exit remains partially or fully open	Migration of DME into engine induction system from purge tank potentially causing combustion knock and excessive engine speed (limited by overspeed trip valve V#5) upon engine startup.	Mechanical failure of valve				
			Valve powered due to an electrical malfunction				
Fu. 2. DME fuel return to induction system turned on (valve powered) - open exit when engine is turned on	Solenoid exit remains in closed position	DME cannot vent into the engine induction system causing the low pressure blow down valve (V#4) to vent the DME return fuel to atmosphere	Mechanical failure of valve				
			Valve not powered due to electrical malfunction				

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System/Item Component Function	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN
5.6 Check valve (CH#2)							
Fu. 1: Valve opens at minimal pressure differential to allow DME into engine induction system	Valve does not open	DME cannot vent into the engine induction system causing the low pressure blow down valve (V#4) to vent the DME return fuel to atmosphere	Mechanical failure of valve - sticking/seizure/particle deposition				
Fu. 2: Valve closes at minimal pressure differential to prevent air from entering into the purge tank and creating a combustible mixture of DME and air	Valve does not close	No effects unless solenoid valve (SOL#3) fails to close upon engine shutdown. Temperature cycling during storage may allow air to enter the purge tank creating a combustible mixture in the purge tank	Mechanical failure of valve - sticking/seizure/particle deposition				
5.7 Check valve (CH#3)							
Fu. 1: Valve opens at minimal pressure differential to allow DME to flow from the injection nozzle return line into the low pressure DME supply line	Valve does not open	Increasing back-pressure in the injection nozzle return line, eventually preventing the injection nozzle needle from lifting, resulting in engine shutdown	Mechanical failure of valve - sticking/seizure/particle deposition				
Fu. 2: Valve closes at minimal pressure differential to prevent DME in low pressure DME supply line from venting into the purge tank	Valve does not close	DME vents from the low pressure DME supply line as well as from the injection nozzle returns with no significant effect provided that the purge tank has sufficient capacity	Mechanical failure of valve - sticking/seizure/particle deposition				
5.8 Low pressure blow down valve (V#4)							
Fu. 1: Protects DME fuel return system components from excessive pressure	Excessive pressures generated in DME fuel return system	Potential rupture of the purge tank during a fire situation	Malfunction of low pressure blowdown valve (V#4)				
5.9 Metering orifice (MO#1)							
Fu. 1: Restricts the flow of gaseous DME into the engine induction system such that the concentration of DME in the air is below the lean flammability limit of DME/air thereby preventing spontaneous pre-combustion of the DME in the engine's cylinders	Excessive orifice restriction	DME cannot vent into the engine induction system causing the low pressure blow down valve (V#4) to vent the DME return fuel to atmosphere	Deposit buildup in the metering orifice - unlikely since the fuel is filtered just prior to the orifice				
5.10 Metering orifice (MO#2)							
Fu. 1: Restricts the flow of DME from the injection nozzle returns into the purge tank such that most of the DME return enters the low pressure DME supply line with a minimal quantity of DME being returned to the induction system	Excessive orifice restriction	Reduced rates of venting from the injection nozzle returns into the purge tank upon engine shutdown	Deposit buildup in the metering orifice - unlikely since the fuel is filtered just prior to the orifice				

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System/Item Component Function	Potential failure	Effect of failure	Cause of failure	Occurrence			
				O	I	D	RPN
6. Diesel fuel control system							
6.1 Solenoid valve (SOL#1) - 2 position/2 way valve							
Fu. 1: Diesel fuel lubrication system shut off (valve not powered) - closed exit when engine is shut off	Solenoid exit remains partially or fully open	No effects on system if diesel fuel lubrication pump shuts off. Else slow migration of diesel fuel from the shuttle valve into the DME high pressure injection line causing engine startup on a mixture of diesel fuel and DME	Mechanical failure of valve				
			Valve powered due to an electrical malfunction				
Fu. 2: Diesel fuel lubrication system turned on (valve powered) - open exit when engine is turned on	Solenoid exit remains in closed position	Reduced shuttle valve lubrication resulting in increased shuttle valve wear and potential seizure	Mechanical failure of valve				
			Valve not powered due to electrical malfunction				
6.2 Check valve (CH#1)							
Fu. 1: Valve opens at minimal pressure differential to allow diesel fuel lubrication of shuttle valves	Valve does not open	Reduced shuttle valve lubrication resulting in increased shuttle valve wear and potential seizure	Mechanical failure of valve - sticking/seizure./particle deposition				
Fu. 2: Valve closes at minimal pressure differential to prevent backflow of diesel fuel from shuttle valve during injection period	Valve does not close	Fu. 2: Backflow of diesel fuel away from the shuttle valve during the injection period reducing shuttle valve lubrication	Mechanical failure of valve - sticking/seizure/particle deposition				
6.3 Heat exchanger (diesel fuel)							
Fu. 1: Minimize heat buildup in the diesel fuel supply system (closed loop system)	Heat exchanger fails to cool diesel fuel adequately	Excessive diesel fuel temperatures in supply and lubrication systems causing reduced shuttle valve and fuel pump lubrication, deposition in injection pump and barrel/plunger sticking/seizure	Blockage/contamination of heat exchanger cooling surface				

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Appendix G

AVL LIST GMBH Report No. BE 0472
Design Guidelines for Dimethyl Ether Injection Systems

AVL LIST GMBH

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FAX +43 316 787 - 400

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Mr. Gary D. Webster
17 Fitzgerald Road, Suite 102
Nepean, Ontario K2H 9G1
Canada

Unser Zeichen / our reference	Durchwahl / extension	Fax direkt / direct fax	Graz,
BE/Ofner/pr	613	134	19-Apr-1999

Report No. BE 0472

Dear Mr. Webster:

Enclosed please find one copy of Report No. BE 0472 concerning R&D Task 3 "Design Guidelines for Dimethyl Ether Injection Systems" carried out within the activities of Annex XIV of the IAE/AMF.

We would appreciate receiving your comments concerning the contents and/or suggestions for any passages in this report you would like to have changed.

Thank you in advance for your assistance.

Best regards,

AVL LIST GMBH

Herwig Ofner

Enclosures

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REPORT BE 0472
MARCH 1999

IEA / AMF
ANNEX XIV
DIMETHYL ETHER AS AN AUTOMOTIVE FUEL

R&D TASK 3
DESIGN GUIDELINES FOR
DIMETHYL ETHER INJECTION SYSTEMS

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Distribution

Participating Countries Annex XIV of IEA/AMF

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IEA / AMF
Annex XIV
Dimethyl Ether as an Automotive Fuel

R&D Task 3
Design Guidelines for Dimethyl Ether Injection Systems

Contents

		Page
1.	Introduction	G-4
2.	Summary	G-5
3.	Conclusions	G-6
4.	Objective and Method of the System Assessment	G-9
5.	Definition of Boundary Conditions and System Features	G-9
6.	Definition and Assessment of Systems	G-12
	6.1 Proposed and Assessed Fuel Injection Systems	G-12
	6.2 General Principles of Hardware Components	G-13
	6.3 Definition of Component Functions and Guidelines for Assessment	G-14
	6.4 System A - Pump Line Nozzle DME Injection System	G-15
	6.5 System B - Shuttle Valve DME Injection System	G-15
	6.6 System C - Common Rail DME Injection System	G-16
7.	List of Figures, Appendix	G-17

1. Introduction

The Research and Development (R&D) Task described in this report has been carried out within the activities of the Annex XIV of the IAE/AMF (International Energy Agency / Implementing Agreement on Alternative Motor Fuels). The objective of this Annex XIV is to investigate the introduction of DiMethyl Ether (DME) as an automotive fuel. The work concentrates on subjects which are of general interest and focuses on establishing a fuel quality standard, fuel cost, operational and safety aspects for DME engines and vehicles and environmental issues.

The Annex XVI is supported by the following ten countries: USA, Finland, Norway, Denmark, Netherlands, Sweden, Canada, Japan, France and Austria. France and Austria are not member countries of the Implementing Agreement AMF, but participate via sponsors (France : IFP, PSA and Renault; Austria : AVL List).

An Annex on DME has been created in 1997 and was prepared since 1996. At the 20th IEA Executive Committee meeting in Harwell, England (spring 1996), the decision was made to organise a DME workshop. This was done by TNO Road-Vehicles Research Institute and the workshop was held in November 1996 at the TNO facilities in Delft, Netherlands. In the course of two further workshops (June 1997 in Delft, February 1998 in Naperville, USA), the subjects and the funding of the activities were finalised, thus the "kick off" of the R&D Tasks took place in Naperville. At the fall meeting 1998, which again took place in Delft, many of the Task reports were ready in a draft version. The final version of this report was presented and delivered during the last (5th) workshop in Graz, Austria, which took place in March 1999.

Within theses activities, seven R&D tasks deal with the following subjects :

Task 1 : Trade-off of fuel quality versus costs
Task 2 : Safety investigations - DME distribution and handling on vehicles
Task 3 : Design guidelines for DME fuel injection systems
Task 4 : DME from renewable feedstock
Task 5 : Life cycle analysis
Task 6 : Cost of DME infrastructure
Task 7 : Operating agent, workshops, newsletter

The following companies (countries) participated in the Task 3 activities :

Advanced Engine Technology Ltd. (Canada)
AVL List GmbH (Austria); Task Leader

AVL Powertrain Eng. (USA)
Renault (France)
Technical University of Denmark (Denmark)

2. Summary

Within the R&D Task 3, general guidelines for the layout and the design of fuel systems for DME were set up. Thus, different types of fuel systems, which fulfil the basic requirements for vehicle application, were assessed. The purpose of the guidelines summarised in this report is to demonstrate and discuss individual items of this new technology.

The work concentrates on the assessment of different system concepts. It demonstrates how far standard engine and fuel injection system technology for Diesel fuel and LPG can be used and shows in which fields new technology is required for DME. Furthermore, the degree of complexity of such systems is demonstrated and possible safety hazards are described.

The assessment is done by a "Failure Mode and Effect Analysis" (FMEA). For this analysis, the individual concepts are prepared according to a standardised scheme. Emphasis is laid on the functional principles and the consideration of all possible system states. It was also agreed among all partners of the task group to include control strategies and basic safety aspects for both the fuel systems and the engine.

During the FMEA meeting, all possible system states were discussed and possible failures and their consequences were listed in the FMEA tables. For the assessment of the failures, their importance was evaluated, the difficulty to detect them and their likelihood to occur. These three criteria were expressed in terms of numbers between 1 and 10. The product of these three numbers is called the "Risk Priority Number (RPN)" and expresses the seriousness of the failure.

At the beginning five different types of systems were proposed by the participants of Task 3:

1. "Shuttle valve concept" in a pump line nozzle diesel injection system (AET Canada)
2. Common rail fuel injection system as published by AVL Austria
3. Common rail fuel injection system as published by AVL Powertrain Engineering USA
4. BOSCH Type diesel common rail system adapted for use with DME (Renault France)
5. "Standard" pump line nozzle diesel injection system adapted for use with DME (TU Denm.)

For the FMEA meeting, only representatives of three systems could get together (systems 1, 2, 5). As these systems represented completely different concepts, it was decided to

generalise them in a way that commonly used components were standardised (e.g. storage tank and DME injection nozzle) and the peculiarities of the individual systems were analysed in more detail. Consequently, it was finally distinguished between the following systems:

System A : "Standard" pump line nozzle diesel injection system adapted for use with DME (TU Denmark.)
System B :"Shuttle valve concept" in a pump line nozzle diesel injection system (AET Canada)
System C : "Common rail" fuel injection system as published by AVL Austria

The FMEA meeting was held on July 9-10, 1998 at AVL Graz (Austria). The FMEA Team was formed by five participants (1 coach from AVL, 2 AVL, 1 AET, 1 TU-Denm.)

3. Conclusions

The conclusions are considered the "Design Guidelines" which represent the results of the task. The assessment method was introduced by Renault (structural analysis) and AVL (system FMEA assessment). It has proven to be a powerful tool and is recommended for further system investigations.

The items listed below have been found during three phases of the work :

Some agreements were already made during the initial phase when the boundary conditions were defined for the individual systems. During that phase, the systems were adapted to the same level of complexity and the participants had to agree on a certain system standard. All participants had practical experience with DME fuel injection systems.

Further conclusions were made at the end of the FMEA meeting.

At the 4th workshop in Delft (Oct. 1998), both the results of the Tasks 2 and 3 were presented and discussed. At that point, further (joint Task 2 and 3) conclusions were agreed which give the most general aspects.

Agreements during definition phase:

- At least for prototype systems, a conditioning system for (low pressure) gaseous DME is required (for preventing DME leakage to escape into the environment and for purging parts of the system after engine shutdown to prevent DME leakage into the engine). Such a conditioning system can be e.g. a purge tank plus compressor or a carbon

cartridge with a suitable device for regeneration. Other devices are possible but have not been assessed.
- The basic system control functions (engine start/stop) are considered because they differ from those for standard diesel fuel systems.
- The systems must consider a fuel temperature control (DME cooler).

Conclusions from the FMEA meeting:

I. General:

- It would be beneficial to isolate (separate) the storage tank from the remaining system and the engine whenever possible (quickly reacting shut off device).
- If pipes or hoses break, care should be taken that only a small amount of DME can escape (small fuel volumes, sensors detect damage, shutdown function of system control concept).
- Many malfunctions of system operation originate from dirt and particles in the fuel system, thus high emphasis must be laid on fuel filtering.

II. System concept:

- The common rail concept represents a relatively new technology. However, as the system has been specifically considered for use with DME, there are no areas with very high risks.
- The pump line nozzle concepts are based on a proven technology, but show some areas of concern, mainly at the plunger barrel of the pump (leakage, seizing).
- The common rail concept has a higher potential for redundancy than the pump line nozzle and the shuttle valve concept.

III. DME gas conditioning system:

- If a fuel system is in the development stage, a device for conditioning low pressure gaseous DME is required (a purge tank and a carbon canister were assessed). Such a device is not necessary for engine operation but for system control (start, stop, emergency shutdown).
- The conditioning system must be very well developed, otherwise it represents more of a risk than a safety precaution.
- Carbon canisters should be designed for higher pressures (similar to purge tanks)
- For carbon canisters, the regeneration and regeneration control are relatively complex.
- No experience exists for the regeneration of DME to the intake air of the engine (effects on HC, CO, misfiring).
- Both conditioning devices have been assessed as critical because they represent new technology and are relatively complex.

Joint Task 2 and Task 3 conclusions:

- The technical issues associated with implementing DME in Diesel engines are not insurmountable.
- Three different system concepts have been assessed (pump line nozzle, shuttle valve, common rail). All concepts were found technically feasible.
- The assessments were based on existing Diesel and LPG technology. Areas which require development have been identified.
- On average, the introduction of new technology means higher risks. However, areas of severe concerns can be avoided as the new technology is aligned to the specific requirements of the new fuel.
- On average, the adaptation of proven Diesel fuel and LPG technology for use with DME shows lower risks but also individual items of high concerns. These have to be considered very carefully and the introduction of new technology in these fields is inevitable.

* * * *

4. Objective and Method of the System Assessment

The establishment of design guidelines for systems is like a walk on a tightrope. On the one hand, care must be taken not to go too much into design details of individual components, and on the other hand, the systems must be comprehensively defined. An other question is how to objectively assess the different system concepts.

For the assessment, a "Failure Mode and Effect Analysis" (FMEA) was chosen which is a powerful and well accepted tool within system analysis and quality engineering. Emphasis is laid on the system aspect, thus the system concepts are assessed with respect to their functions. Design details were considered only as far as changes of system states are concerned.

The system analysis was made according to a standardised scheme. For that purpose, exact boundary conditions and system features had to be defined or, in other words, the system demands were clearly established. In a next step, all system functions were listed in the FMEA sheets and these functions finally were assessed by the FMEA group.

This procedure allows the introduction of personal experience, subjective opinions and spontaneous ideas of the participants. The advantage of having an "international" FMEA meeting was that different concepts were assessed simultaneously. Thus, their analysis was based on the same prerequisites and the evaluated results of the different systems are therefore comparable. The analysis was no "competition" of concepts, but demonstrates advantageous and weak points, shows "forgotten" items but also demonstrates if e.g. safety precautions have been carried too far.

The result of the R&D Task 3 work is a general definition of the demands for a DME fuel system used for automotive application. Furthermore, those areas are identified which require development work for new technology. The conclusions of the system evaluation can be considered as guidelines for the design of such systems.

5. Definition of Boundary Conditions and System Features

With respect to the boundary conditions of the systems, it clearly had to be distinguished between the Task 3 and the Task 2 activities, which deal with the fuel storage and fuel supply on board vehicles and concentrate on safety aspects.

During the Workshop in Naperville (Feb. 1998), Renault Research introduced a method which makes the exact definition of systems possible and also helps to clearly separate the fuel system into individual parts. This method was quickly applied during the meeting and

afterwards worked out in more detail (This method has been developed by Renault and is called "Structural Analysis and Design Technique" SADT).

The basic principle of this method is given in Fig. 1. The figure demonstrates the general procedure of the SADT system definition. The key issue is the system's function which is cited in a box. It requires inputs and outputs and provides a certain service. The service is usually (physically) equivalent to one or more outputs, however not all outputs are services. On the top of the box, the parameters which influence (e.g. control) the function of the system are listed and on the bottom the hardware component is given.

Using this principle, a complex system can be split into any degree of details. Its advantage is that individual parts can be detailed to a high degree of complexity, but in the same representation, other parts may remain on the surface. In this way, details can be assessed without losing the overview on the entire system. This kind of representation also helps to define the interactions between the components (or component groups).

The complete system which was subject to both activities (R&D Task 2 and Task 3) is given in Fig.2. In Fig. 3, the same system is split into more detail. The grey area delimits the system which was assessed in the Task 3 activities. This means that all concepts considered the following items:

Physical components (component groups):

- DME fuel injection system (different types of injection systems were defined)
- DME cooler (heat exchanger)
- Conditioning system for (low pressure) gaseous DME which may be leakage or accumulated gas from purging parts of the system. Such a conditioning system can be e.g. a purge tank plus compressor or a carbon cartridge with a suitable device for regeneration.

Some comments to the DME (gas-) conditioning system:

It is difficult to standardise precautionary measures for the prevention of DME leakage into the environment and into the combustion chambers of the engine. On the one hand, it can be assumed that leakage can be avoided (at least for all static seals) if the sealing concepts are suitable for liquefied gases. On the other hand, this is certainly not the case if standard diesel injection components (e.g. injection nozzles, plunger pumps) are applied. The question is, e.g. how much gas may leak into the cylinder without causing unacceptable effects.

If it is considered that at engine shutdown the injector nozzle stays filled with DME (approx. 200 mm3 liquid DME at 5 bar) then, after a while, the fuel will leak over the injector needle seat into the combustion chamber. The DME quantity of only the nozzle would

already cause a DME concentration in the cylinder which lies well within the explosion limits*. Therefore it is completely unacceptable if the DME in the nozzle holder and the injection line would additionally leak into the cylinder. Beside the safety issues, it must be considered that for automotive use the DME will contain an odour additive, therefore any leakage would mean a smell nuisance.

At the moment, not enough details are known to estimate an acceptable leak quantity. Therefore, it was agreed that DME leakage should be avoided in all cases. This requires the introduction of special equipment as listed above.

Input streams:

- Fuel supply of liquid DME at a pressure which is above the saturation pressure (referred to the temperature in the storage tank). If held at this temperature, it can be assumed that there is no tendency to cavitation at the intake to an injection pump.
- Gaseous DME (leakage) could also originate from the storage system. This gas would also be conditioned in the low pressure gas conditioning system (optional)

Output streams:

- Liquid DME which is injected into the combustion chamber of the engine (="service")
- Gaseous DME which is mixed to the intake air of the engine (optional)

Parameters:

- Temperature control: All systems must have a fuel temperature control, e.g. surplus liquid DME can be returned over a cooler as indicated in Fig. 3. There can be other solutions, for example the fuel can be returned to the tank, if the heat balance of tank allows such a solution.

- Control functions (necessary):
  - Engine start/stop function (e.g. fuel supply on/off by a solenoid valve)
  - Control of fuel metering (power demand)
  - Timing control (adapted for the low speed of sound of DME)

- Control functions (optional):
  - Special safety control functions
  - Special diagnostic functions

* Explosion limits in air 3.4 – 17% (vol)
Density liquid DME 660 kg/m³ (5 bar, 20 °C)
Density DME gas 1.9 kg/m³ (1 bar, 20 °C)

Additional control and diagnostic functions could improve the safety standard and the engine's operational reliability. Their advantages could possibly be illustrated by the FMEA assessment numbers, however, it should be considered that a too high increase in complexity could also worsen a system.

6. Definition and Assessment of Systems

6.1. Proposed and Assessed Fuel Injection Systems

At the "Kick Off"- meeting in Naperville, the following types of systems were proposed for assessment :

1. "Shuttle valve concept" in a pump line nozzle diesel injection system (AET Canada)
2. Common rail fuel injection system as published by AVL Austria
3. Common rail fuel injection system as published by AVL Powertrain Engineering USA
4. BOSCH Type diesel common rail system adapted for use with DME (Renault France)
5. "Standard" pump line nozzle diesel injection system adapted for use with DME (TU Denm.)

For the FMEA meeting, only representatives of three systems could get together (systems 1, 2, 5). As these systems represented completely different concepts, it was decided to generalise them in a way that commonly used components were standardised (e.g. storage tank and DME injection nozzle) and the peculiarities of the individual systems were analysed in more detail. Consequently it was finally distinguished between the following systems :

System A : "Standard" pump line nozzle diesel inj. system adapted for use with DME (TU Denmark.)
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System C : Common rail fuel injection system as published by AVL Austria

The FMEA meeting was held on July 9-10, 1998 at AVL Graz (Austria). The FMEA Team was formed by :

E. Mungenast	AVL (Austria), Production Engineering, FMEA Coach
H. Ofner	AVL (Austria) , FIE and system hydraulics
R. Schneider	AVL (Austria), Vehicle electronics and control systems
S.C. Sorenson	TU (Denmark), Engine development
G. Webster	AET (Canada), Engine development

The three systems (A,B,C, see above) represent three completely different concepts. System A is a reasonable approach to the problem as it uses "Standard" Diesel fuel equipment. Many authors of published literature used such types of fuel injection systems, at least for basic research work carried out in laboratories and engine test cells. However, one severe problem always was the leakage into pump housing, combustion chamber and to the environment. This has to be prevented by special measures in order to fulfil the boundary conditions.

The system B introduces an interesting approach for preventing the leakage. It contains DME only in some individual parts of the system (injection line, injector). The injection pump delivers Diesel fuel, which, over a "Shuttle Valve" , displaces the DME. Both the pumping, fuel metering and injection control is done with Diesel fuel.

The system C uses a common rail concept which is especially designed for DME. Thus, it represents a comprehensive approach with high flexibility in all control features.

These different principles offered the possibility to start with a simple, well known technology (system A) which successively was extended by special DME equipment (system B and system C). All systems were reduced to their functional principles in order to standardise them and to get comparable degrees of system complexity. The DME storage tank and the fuel injection nozzles were common for all three systems.

6.2. General Principles of Hardware Components

Once the boundary conditions and the system concept have been defined, a (simplified) scheme of hardware components can be set up. The objective of the assessment is the system functions (and no design details), therefore all functions of the components must be determined. For this purpose, the principles of some components must be defined.

Solenoid valves

The solenoid valves are poppet valves as demonstrated in Fig.4. As an example, this figure shows a 2 positions / 3 way valve. It is important that the valve connections are marked (Supply, Exit etc) and that all possible connections are listed. If solenoid valves are applied in a system it must be considered that they have to be actuated. This can be done manually directly by the driver, e.g. by turning the key or pressing a button or indirectly by an electronic controller. If a controller is used, it must be included to the FMEA, however, for reasons of simplicity it is kept in a very general form.

Check valves and mechanical pressure regulators

The principle of check valves and mechanical pressure regulators is given in Fig. 5.

Electronically controlled pressure regulators

The principle of an electronically controlled pressure regulator is also shown in Fig. 5. It consists of an actuator, a sensor and an electronic control unit. Please note that the pressure sensor also includes the cable to the control unit and the control unit also the cable to the actuator!

Fuel system control

The basic engine control features like engine start / stop must also be considered. In most cases, solenoid valves, starter motor, supply pump etc. are actuated according to "actions" like, for example, switching the key off -> on. The basic control features are defined by the state diagram and the state transition diagram. The state diagram defines the individual states (e.g. solenoid valves can be "on" or "off") at different conditions of operation (e.g. "park", "crank engine", or "engine operation"). The state transition diagram defines all possible changes of states (e.g. a change from "crank engine " to "engine operation" is possible but not the vice versa transition). The state definitions are given for all assessed systems in the figures. A state transition diagram is given only once (for system C), but they are analogous for the other systems.

6.3. Definition of Component Functions and Guidelines for Assessment

The component functions are defined and cited into special FMEA sheets. These are tables which show the functions, the potential failure of the function and it's effects and causes. In this well ordered list, the individual functions and failures can be assessed (from the FMEA team). This means that the team gives evaluation numbers to the O (=occurance of a failure), I (=importance) and D (=detectability) of the individual items. These numbers result in the "Risk Priority Number" (RPN = O*I*D). Evaluation guidelines are listed in Fig.6.

There are some additional aspects which should be realised:

- No combination of failures is considered.
- Mechanical and electrical failures are generalised and depend on the individual component.

- The fuel injection systems are considered for multi cylinder applications. Therefore, the stop of fuel delivery does not necessarily mean stop of engine.
- Seals are contact seals (e.g. O-rings), fixed metal fittings (e.g. clamping rings) or narrow gaps (e.g. plunger / plunger barrel).
- Safety risks according to leakage do not distinguish between high or small amounts of leakage.

6.4. System A – Pump Line Nozzle DME Injection System

The scheme is given in Fig. 7. The fuel is stored in a pressure tank where the DME is kept at saturated state. From there, the liquid fuel is delivered to the fuel injection system by a supply pump. A solenoid valve (V1) closes / opens the connection from the tank to the system. V1 is a 2 positions / 3 way valve as demonstrated in Figure 4. If V1 is "off", it closes the connection between tank and system and opens the system to the gas conditioning system. If V1 is "on ", DME can be supplied from the storage tank into the system and the connection to the gas conditioning system is closed.

In their principle, both the injection pump and the injection nozzle are standard diesel fuel injection equipment. That is why e.g. the pump camshaft housing must also be ventilated to the gas conditioning system because an undefined amount of DME leaks via the gap between plunger and barrel into this chamber.

As gas conditioning system, a charcoal canister is considered. For regeneration, air is supplied to the canister and the DME – air mixture is added to the intake air of the engine. The regeneration must be controlled because no DME may escape during engine shut-down. Furthermore, the DME which is added to the intake air must be carefully metered.

6.5. System B – Shuttle Valve DME Injection System

The shuttle valve concept avoids the problem of DME leakage into the pump housing by separating the DME from the pump (and thus also from the fuel metering device, timing control etc., see Fig. 9). The injection pump delivers diesel fuel to the shuttle valve which transmits the injection pulse to the DME.

For the system assessed, the same storage device (tank and V1) and the same gas conditioning system as described for the Jerk pump system (system A) was considered.

6.6. System C – Common Rail DME Injection System

The storage tank and the fuel shut-off device (V1) is identical to those described in system A and B, see Fig. 11.

For conditioning the low pressure gaseous DME, a "purge system" is applied. The purge tank is a pressure tank in which the pressure is kept below saturation pressure in order to keep the DME in a gaseous state. After engine shutdown, the liquid DME which is in the fuel injection system, is expanded into this tank and thus evaporates. For controlling the pressure in the purge tank, a compressor is installed which recompresses the gas into the storage tank. This compressor operates in an on / off mode and is automatically controlled by a control unit. As soon as the purge tank pressure sensor detects a certain "maximum" pressure level, the controller switches the compressor "on" and stops it as soon as a "minimum" is reached again.

In the fuel system, the supplied liquid DME is cooled in a heat exchanger and afterwards delivered to two fuel pumps. The high pressure pump (hp_p) is driven by the engine and builds up the rail pressure (approx. 250 bar). The rail pressure is controlled by an electronically controlled pressure regulator (hp_epr).

The second pump (circulation pump c_p) builds up the residual pressure in the injectors and circulates the fuel for cooling purpose. The residual pressure is adjusted by a mechanical pressure regulator (pr_2).

The fuel injection is controlled by the injection solenoid valve (inj_V). This valve closes the high pressure to the injector if it is in "off" state and, at the same time, opens the injectors to the "control line". If the valve is "on", it opens the high pressure to the injectors and closes the "control line".

The fuel injectors are standard Diesel fuel injection nozzle holder / nozzle configurations.

The system is described in more detail in published literature (e.g. SAE 981158 "Dimethyl Ether as Fuel for CI Engines – A New Technology and its Environmental Potential"). For this FMEA it had to be simplified, however the principle has stayed the same.

7. List of Figures, Appendix

Fig.	
1	General structure for definition of system
2	Overview of DME fuel system
3	Boundary conditions for DME fuel injection system
4	Design principles of solenoid valves
5	Design principles of electronic pressure regulator and mechanical pressure regulator
6	Specific RPN evaluation rules
7	Scheme of system A "jerk pump"
8	Definition of system states, system A
9	Scheme of system B "shuttle valve"
10	Definition of system states, system B
11	Scheme of system C "common rail"
12	Definition of system states, system C
13	State transition diagram, system C

Appendix A: FMEA evaluation tables

A1	DME storage and supply (systems A,B,C)
A2	DME injection nozzle (systems A,B,C)
A3	Injection system (system A)
A4,5	Control system (system A
A6	DME gas conditioning system (system A)
A7,8,9	Injection System (system B) Control + gas conditioning system analogous system A
A10,11,12	Injection system (system C)
A13,14,15	Control system (system C)
A16,17	DME gas conditioning system (system C)

BE 0472
Fig. 1

Fig. 1 : General structure for definition of system

AVL Graz, Austria
Mar 1998 / Ofner

DME fuel system ; overview complete system (1)

Fig. 2 : Overview of DME fuel system

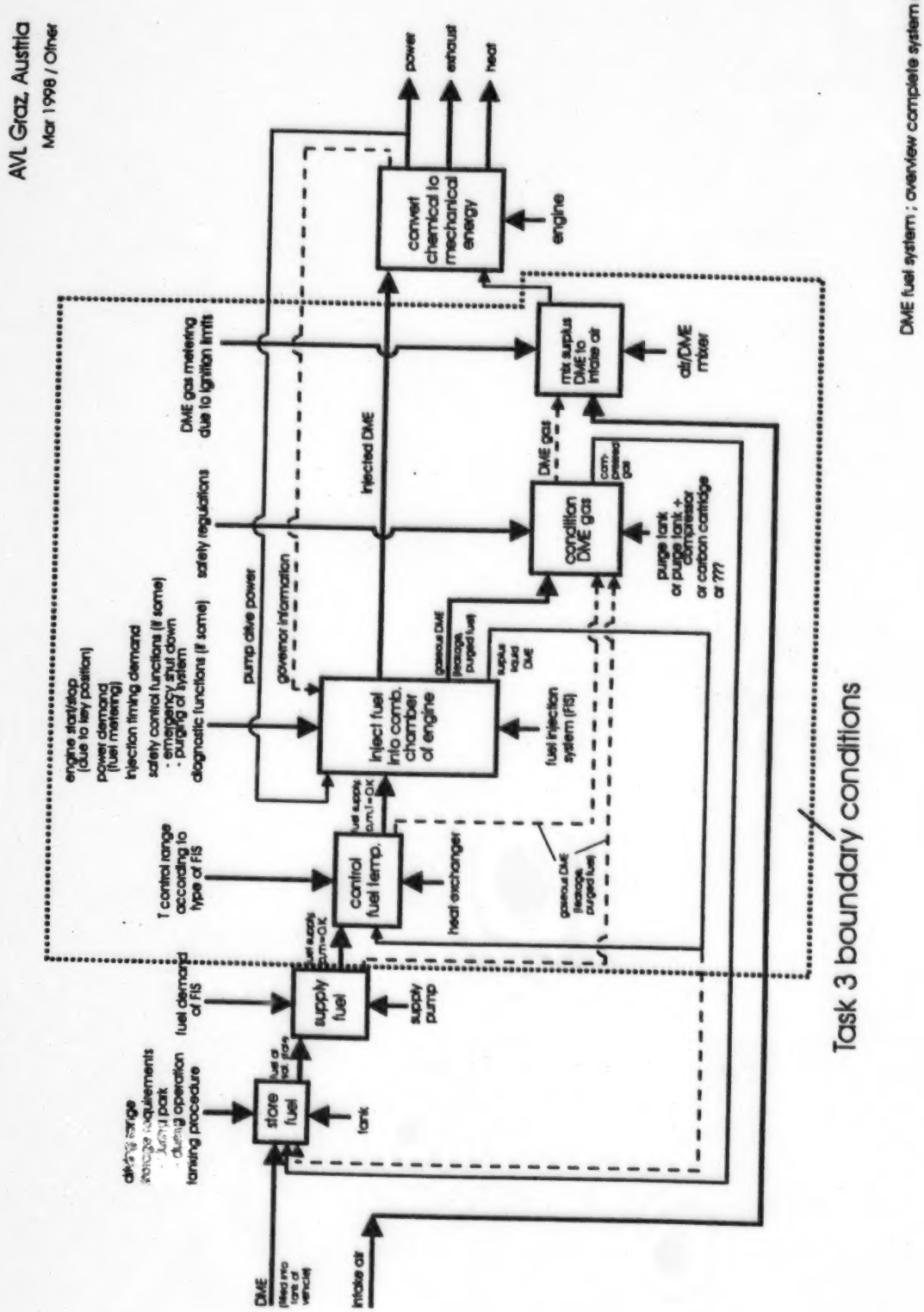
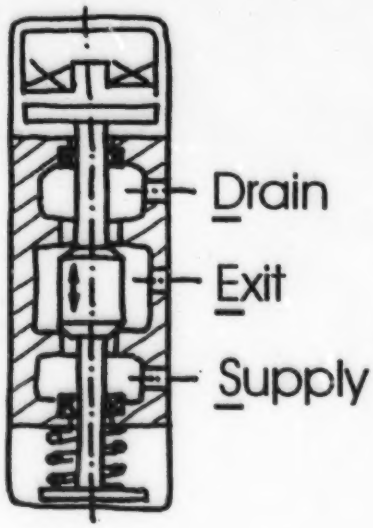


Fig. 3 : Boundary conditions for DME fuel injection system

2 position / 3 way solenoid valve



Assessed valve body positions of 2 position / 3 way solenoid valve (V1) :

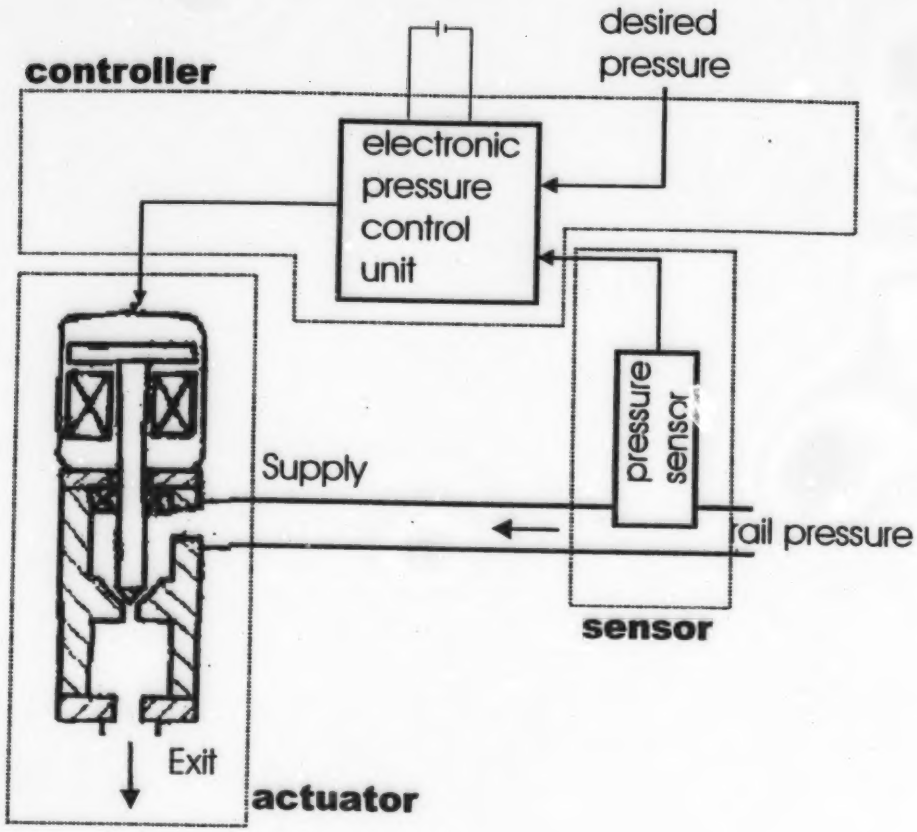
SE	SD	ED	valve body	
closed	closed	open	at lower seat	(valve not powered)
open	closed	closed	at upper seat	(valve powered)
open	open	open	between seats	
closed	closed	closed	blocked	

2 position / 2 way solenoid valve; Normal Closed;
(same principle as above but no Drain port)

Assessed valve body positions of 2 position / 2 way solenoid valve :
(valves for regeneration of charcoal V2, V3) :

SE	valve body	
closed	at lower seat	(valve not powered)
open	at upper seat	(valve powered)

Fig. 4 : Design principles of solenoid valves



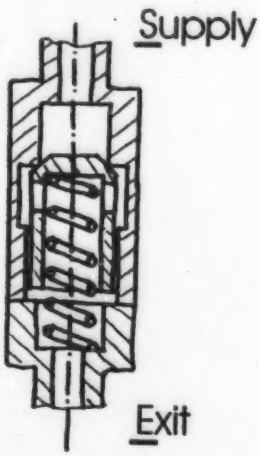


Fig. 5 : Design principles of electronic pressure regulator and mechanical pressure regulator (= same principle as check valve)

Graz, 08.07.1998
„FMEA/EU-DME.doc"
E. Mungenast

Subject: Specific RPN-Evaluation roles for R&D Task 3
„Design Guidelines"

To tune the general FMEA evaluation system to the concerned application the following items are changed according to our experience and the current task:

1. Occurrence of failure

High	7
neutral, no agreement	5
Low	2

2. Importance of failure

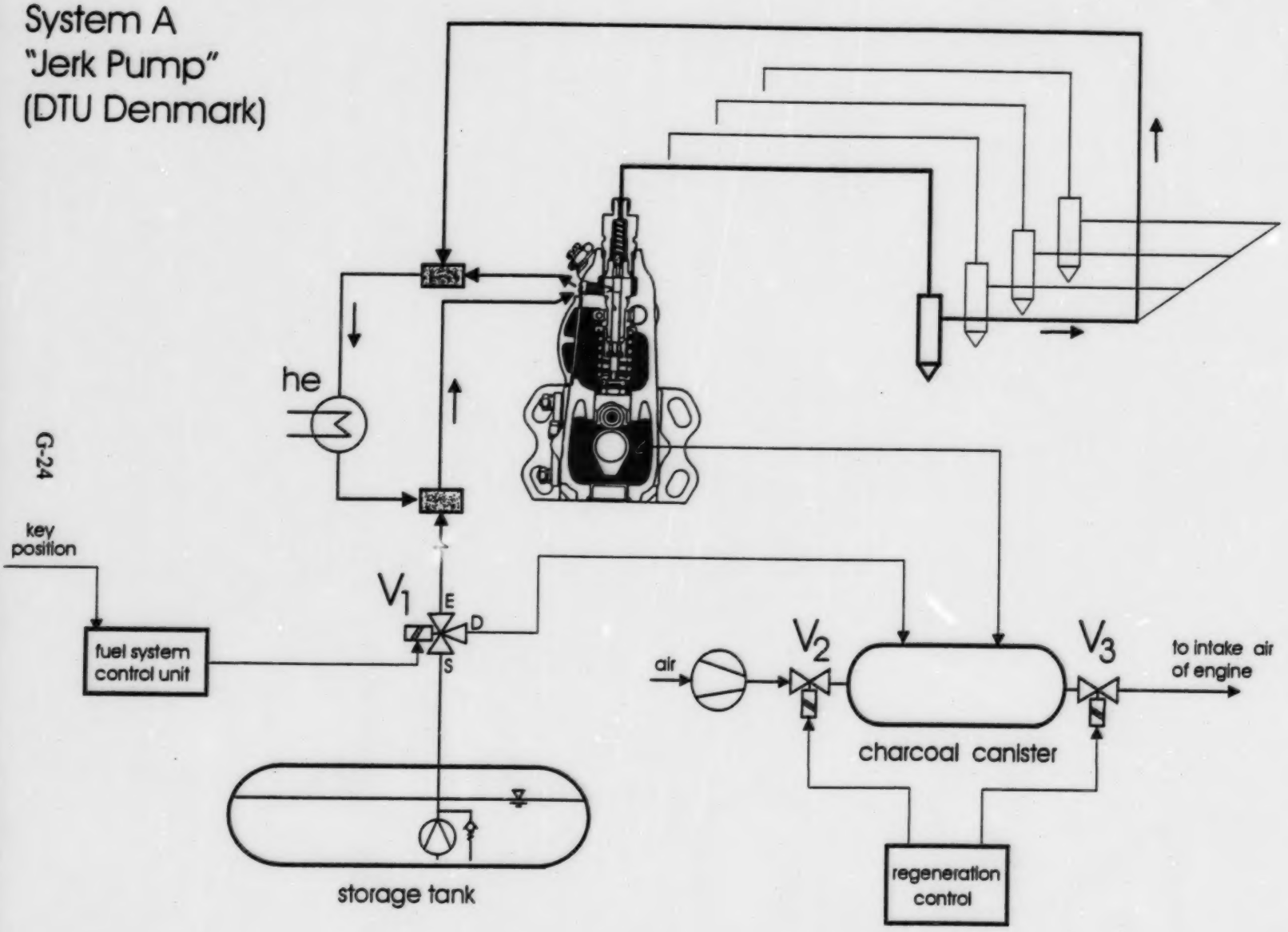
Safety for public	10
Leakage	8
Engine destruction	9
Break down	7
Service necessary, now	5
later	4

3. Detection of failure

Like in general system

BE 0472
Fig. 6

System A
"Jerk Pump"
(DTU Denmark)

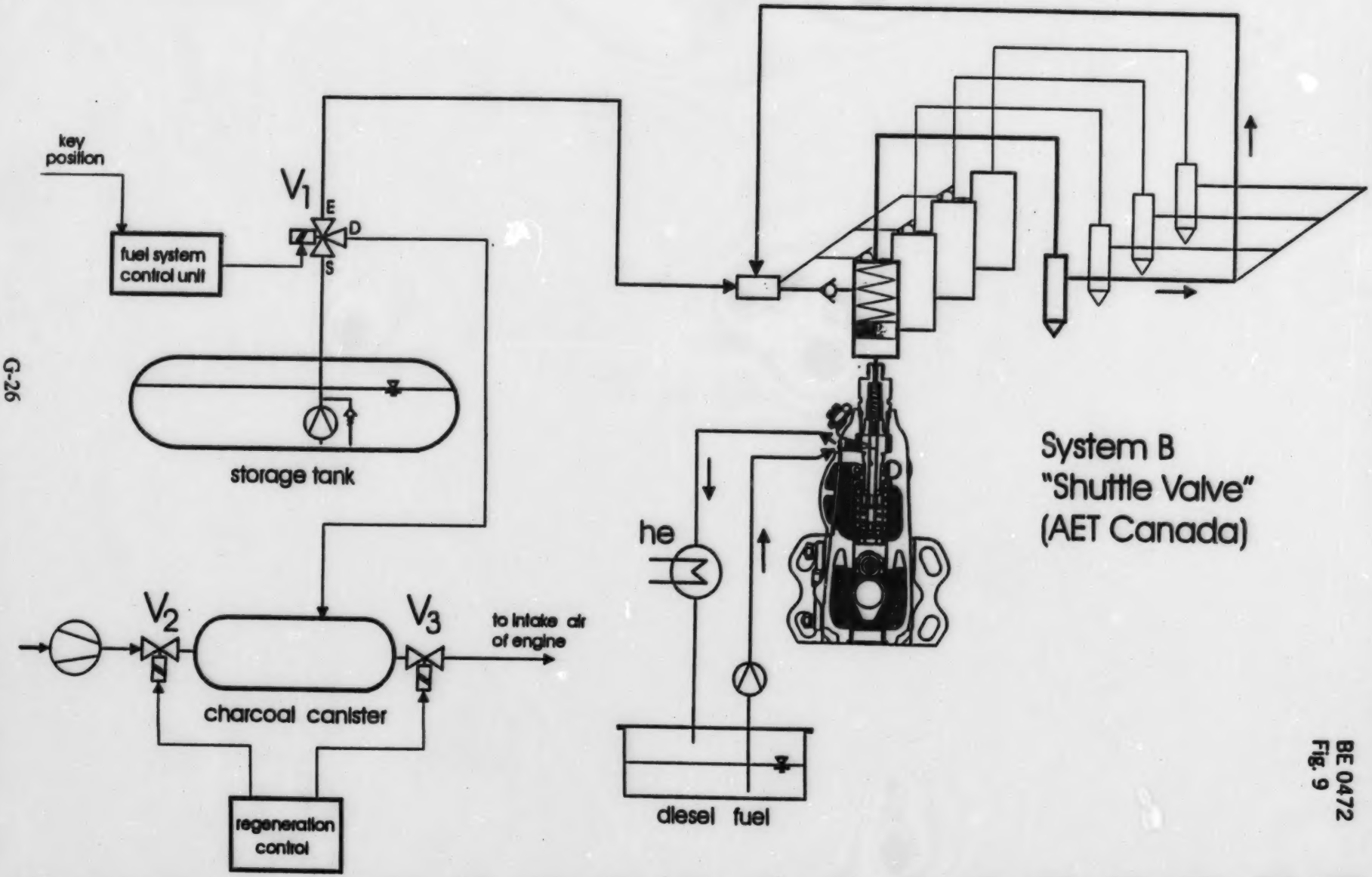


G-24

BE 0472
Fig. 7

State	Key	Speed	Pedal	V1 (system filling)	Fuel Supply Pump	Charcoal Regeneration (V2,V3,Air)	Starter Motor
Park	Off	Low	-	Off	Off	Off	Off
Ready for Start	On	Low	-	On	On	Off	Off
Crank Engine	Start	Low	-	On	On	Off	On
Engine operation "low"	On	High	Low	On	On	Off	Off
Engine operation "high"	On	High	High	On	On	On	Off

System A (Jerk Pump) : Definition of system states



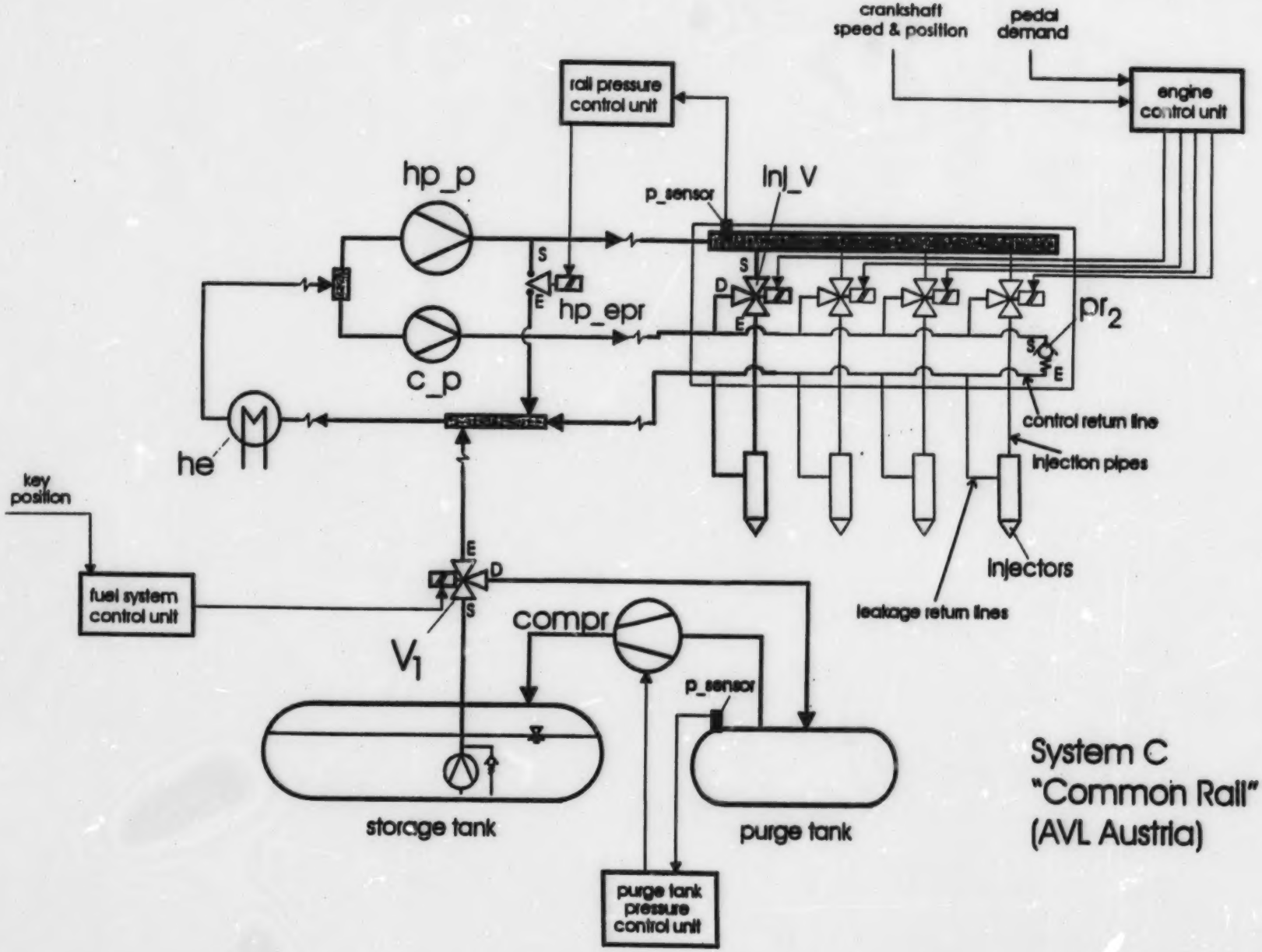
System B
"Shuttle Valve"
(AET Canada)

G-26

BE 0472
Fig. 9

State	Key	V1 (DME system filling)	DME Fuel Supply Pump	Diesel Fuel Supply Pump (+lubrication system)	Charcoal Regeneration (V2,V3,Air)	Starter Motor
Park	Off	Off	Off	Off	Off	Off
Ready for Start	On	On	On	Off	Off	Off
Crank Engine	Start	On	On	On	Off	On
Engine operation	On	On	On	On	On	Off

System B (Shuttle Valve) : Definition of system states

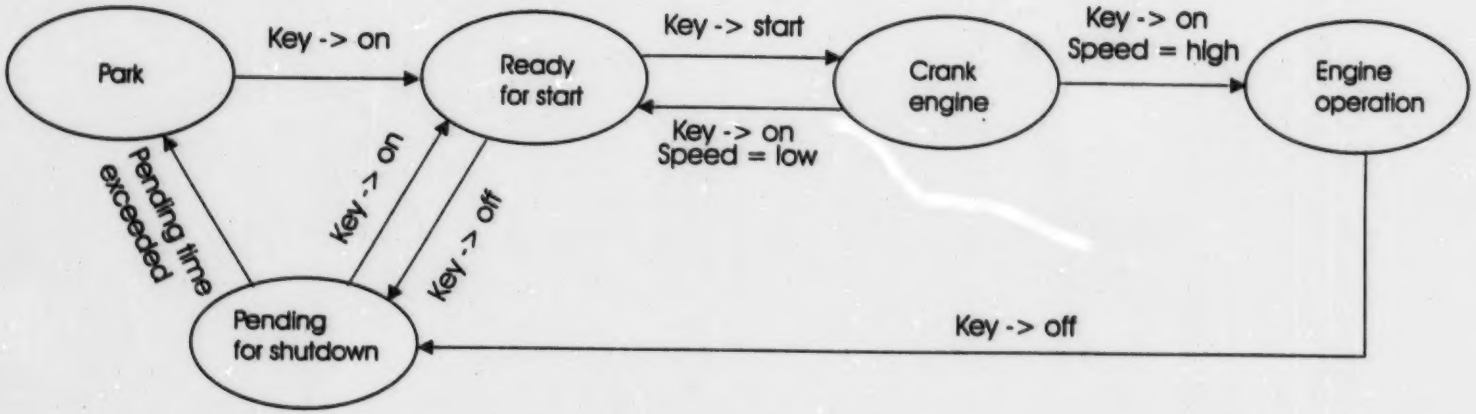


G-28

BE 0472
Fig. 11

State	Key	V1 (DME system filling)	DME Fuel Suppl. Pump	Circu-lation Pump	Control Units			Starter Motor
					Rail Pressure	Engine Control	Purge Compres.	
Park	Off	Off	Off	Off	Off	Off	Off	Off
Ready for Start	On	On	On	Off	On	On	On	Off
Crank Engine	Start	On	On	On	On	On	On	On
Engine operation	On	On	On	On	On	On	On	Off
Pending for shutdown	Off	On	Off	Off	Off	Off	Off	Off

System C (Common Rail) : Definition of system states



State transition diagram; System C

DME Storage and Supply (A+B+C)

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
1. Fuel storage system (storage tank + assy., supply pump,								
pipes to fuel injection system)								
Fu.1: Delivers liquid DME from storage tank to fuel injection system on engine (supply pump = ON). DME pressure is approx. 5 to 15 bar above saturation pressure	Fuel delivery rate too low ; supply pressure too low	DME pressures in system drop, partial evaporation of DME, unstable engine operation, engine stops	Failures in hydraulic part of supply pump (valves, plungers, diaphragms, sealings, etc.)	5	7	2	70	
			Mechanical or electrical failures in drive of supply pump					
			Supply line blocked					
Fu.2: Stops fuel delivery during engine stop (supply pump = OFF); protects tank + pipes from excessive pressure (e.g. by pressure reliefe valves)	Fuel delivery during engine shutdown;	No effects on system if V1, V3 and injection solenoid valves are O.K.	Mechanical or electrical failures in control valves of storage tank	3	4	9	108	
	Excessive pressure due to temperature increase (e.g. in supply line)	Break of components (e.g. supply line), DME escapes from system	Pressure reliefe valves do not work					

BE 0472
App. A1

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
2. Fuel injection nozzle								
Fu.1: Opens orifice to combustion chamber for fuel injection if pressure inside nozzle has exceeded Needle Opening Pressure (NOP)	Orifice stays closed	No fuel injection	Needle hangs in closed position (mechanically)	2	4	5	40	
			Pressure in nozzle spring chamber (=needle back pressure) has increased, e.g. due to blocked ventilation line	1	4	5	20	
Fu.2: Closes orifice to combustion chamber if pressure inside nozzle is below NOP	Orifice is open even if nozzle pressure is below NOP	Continous (uncontrolled) fuel injection	Needle hangs in open position (mechanically)	7	10	4	280	Severe safety issue ! OBD, Emergency shutdown !
			Particles at needle seat					
			Leakage					

DTU Jerk Pump (A) ; Inj. Sys.

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.(A) Fuel injection system								
3.1 High Pressure Jerk pump								
Fu1: Delivers fuel to the nozzle	Does not deliver because of plunger seizure	Unstable engine operation, Loss of engine control	Plunger seizure	8	10	4	320	Materials and Lubricants must be developed
	Does not deliver because of leakage at plunger	Unstable engine operation, leakage of DME into pump housing	Wear of Plunger	8	8	8	512	
Fu2: Generatre the high pressure fuel to the engine	Does not generate adequate pressure	Unstable engine operation, leakage of DME into pump housing	Wear of Plunger	8	8	8	512	
		Unstable engine operation, leakage of DME into pump housing	Overheating of the pump	5	7	3	105	
Fu3: Meter the fuel	Does not meter the fuel	Unstable Operation	Plunger seizure	8	10	4	320	
		Engine Stops	Mechanical failure on rack	3	7	3	63	
3.2: Fuel injection control devices								
Fu1: Shut off fuel injection (zero metering)	Does not work	Unstable operation	Mechanical Failure	8	10	4	320	
		Engine does not stop	Mechanical Failure					
Fu2: Control the injection timing	Does not work	Lower engine performance	Mechanical Failure	2	5	8	80	
3.3 Delivery Valve								
Fu1: Determines the residual pressure in the line	Does not work	Loss of Performance	Damage to valve seat	7	5	8	280	Critical for Wear

BE 0472
App. A3

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
4.(A) Fuel control system								
4.1 Solenoid valve V1: (2 position / 3 way valve)								
Fu. 1: Fuel supply shut off (not powered) cl.SE, cl.SD, op.ED	op.SE, cl.SD, cl.ED	Uncontrolled filling of fuel system	Valve body hangs in open SE position (mechanically)	2	6	8	96	
			Valve powered (e.g. short cut to ground)					
	op.SE, op.SD, op.ED	Short circuit storage to purge tank and uncontroled filling of fuel system	Valve body hangs between seats	6	10	8	480	Filter in supply line ! Take care on seals at valve body !
			Leakage					
	cl.SE, cl.SD, cl.ED	Filling and purging of system is disabled	Blocked by particles	2	7	2	28	
Fu. 2: Fuel supply switched on (valve powered) op.SE, cl.SD, cl.ED	cl.SE, cl.SD, op.ED	No fuel supply	Valve not powered (electrical failures)	5	7	2	70	
			Valve body mechanically blocked					
	op.SE, op.SD, op.ED	see Fu. 1					o.s.	
	cl.SE, cl.SD, cl.ED	see Fu. 1					o.s.	

BE 0472
App. A4

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
4.2. Fuel Control Unit								
1. Park -> Ready to Start	does not change state							Changes of system states are given in the STATE TRANSITION DIAGRAM
2. Ready to Start ->Park	-- " --							System changes due to state transitions are given in the STATE DIAGRAM
3 Ready to Start -> Crank	-- " --							No numbers were specified because changes of system states refere to individual components which were assessed elswere (e.g. functions of V1 etc.)
4. Crank - > Ready to Start	-- " --							
5. Crank -> Engine Operation rack low	-- " --							
6. Crank -> Engine Operation rack high	-- " --							
7. Engine Operation rack low - > Engine Operation rack high	-- " --							
8. Engine Operation rack high -> Engine Operation rack low	-- " --							
9. Engine Operation rack high -> Park	-- " --							
10. Engine Operation rack low - > Park	-- " --							

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
5. Evaorpative/Leakage control System								
5.1 Air Source for Regeneration								
Ful: Supply Regeneration Air to Canister	No Supply air	High Emisions, canister breakthrough	Plugging	3	6	8	144	
5.2 Canister								
Ful: Temporary storage of purged and leaked DME from system	Disabled Temporary Storage of purged DME	Slightly high combustion emissions for a short time	Poisonsing/deterioration of activated Charcoal	3	6	8	144	
5.3 Air Inlet Valve (V2)								
Ful: Control the purge time	Does not	Small amount of leakage to the enviromment and the engine	Hydraulic, electrical failure, sticking	3	10	9	270	
5.4 Air Outlet Valve (V3)								
deliver of DME into the intake manifold (breakthrough of canister)	Does not	Small amount of leakage to the enviromment and the engine	Hydraulic, electrical failure, sticking	3	10	9	270	

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App. A6

System/Item Component Function	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.(B) Fuel injection system								
3.1 Diesel fuel supply system (tank, supply pump, ...)								
Fu1: Delivers diesel fuel from the tank to the injection pump	Fuel delivery rate too low / supply pressure too low / fuel aeration	Insufficient diesel drawn into injection pump causing reduced shuttle valve displacement, erratic engine operation, engine shutdown	Mechanical / hydraulic failure	2	7	2	28	
			Supply line and/or filters blocked					
			Fuel tank empty					
			Air leak in diesel fuel supply line or pump					
Fu2: Delivers diesel fuel to the shuttle valves for lubrication	Fuel delivery rate too low / supply pressure too low / fuel aeration	Reduced shuttle valve lubrication resulting in increased shuttle valve wear and potential seizure	Mechanical / hydraulic failure	2	7	2	28	
			Supply line and/or filters blocked					
			Fuel tank empty					
			Air leak in diesel fuel supply line or pump					
Fu3: Stops fuel delivery to the shuttle valve at engine shutdown	Fuel delivery during engine shutdown	diesel fuel mixed to DME	Mechanical / hydraulic failure	2	7	2	28	
		charcoal poisoned by diesel fuel						

BE 0472
App. A7

System/Item Component Function	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.2: Diesel fuel injection pump								
Fu1: Supplies high pressure diesel fuel to activate shuttle valve system	Does not supply ...	Erratic engine operation	Insufficient diesel fuel supplied to tank	4	10	4	160	
		Engine does not start / operate	Aeration of diesel					
		Loss of engine control	Seizure of plunger					
			Insufficient lubrication of pump					
Fu2: Generates high pressure diesel / DME	Does not generate ...	Erratic engine operation	Insufficient diesel fuel supplied to tank	2	7	3	42	
		Engine does not start / operate	Aeration of diesel					
			Cavitation (DME)					
Fu3: Meters the fuel	Does not generate ...	Unstable operation	Plunger seizure	8	10	4	320	
		Engine stops	Mechanical / hydraulic failure					
3.3: Fuel injection control devices (rack of diesel pump)								
Fu1: Shut off fuel injection (zero metering)	Does not work	Unstable operation	Mechanical Failure	8	10	4	320	
		Injection does not stop						
Fu2: Control the injection timing	Does no. work	Lower engine performance	Mechanical Failure	2	5	8	80	

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.3 Shuttle valve Diesel fuel / DME								
Fu1: Displacement of shuttle valve causes rapid buildup of DME pressure	Shuttle valve stays open	No DME delivery to nozzle, engine does not start / operate	Shuttle valve seizure from insufficient lubrication	6	7	2	84	
	Shuttle valve stays closed							
Fu2: Provides a sealed interface between diesel fuel and DME	Shuttle valve leaks	Erratic engine operation	Valve seat wear	7	6	4	168	
		Diesel mixed to DME	Excessive clearance between shuttle valve and barrel					
			Deposits on valve seat					
			Valve seat wear					
3.4 DME high pressure check valve								
Fu1: Valve opens at minimal pressure differential to allow DME from supply line to enter high pressure injection line	Check valve stays closed	DME does not transfer from supply line into high pressure injection line	Blockage of check valve	3	5	8	120	
	Shuttle valve stays closed	Erratic engine operation	Seizure of check valve					
Fu2: Check valve closes at minimal pressure differential preventing injection pulse in the high pressure injection line from transferring into DME supply line	Check valve leaks / stays open	High pressure injection pulse weakened as a portion of pulse enters low pressure supply line	Poor fuel lubricity causes excessive wear at the valve seat	6	5	8	240	
		Erratic engine operation	Deposits on valve seat					
			Seizure of check valve					

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.(C) Fuel injection system								
3.1 Injection solenoid valve inj_V (2 position / 3 way solenoid valve)								
Fu. 1: High pressure fuel supply to injectors shut off (not powered) cl.SE, cl.SD, op.ED	op.SE, cl.SD, cl.ED	Uncontrolled fuel injection	Valve body hangs in open SE position (mechanically)	2	10	5	100	
			Valve powered (e.g. short cut to ground)					
	op.SE, op.SD, op.ED	Continuous fuel flow from high pressure rail into control line, high pressure can (possibly) not be held	Valve body hangs between seats	3	7	8	168	
			Leakage					
			Bouncing					
Fu. 2: Fuel injection switched on (valve powered) op.SE, cl.SD, cl.ED	cl.SE, cl.SD, op.ED	No fuel injection	Valve not powered (electrical failures)	6	5	8	240	OBD !!!
			Valve body mechanically blocked					
	op.SE, op.SD, op.ED	see Fu. 1						
	cl.SE, cl.SD, cl.ED	see Fu. 1						

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.2 Engine control system								
3.2.1 Engine speed and position sensor (plus sensor wheel etc.)								
Fu. 1: Detects speed and position of engine crankshaft (possibly additionally of camshaft), converts it into electrical signal and transmits it to engine control unit	Detects wrong speed and position	Engine control fundamentally disturbed	Sensor device (or parts thereof) damaged (mechanically)	2	4	5	40	
	Wrong conversion of speed and position to electrical signal		Wrong calibration					
	Transmits wrong (or no) signal to engine control unit		Electrical failure (broken cable, shortcut to ground, loose contact)					
3.2.2 Fuel temperature sensor								
Fu. 1: Detects temperature in high pressure rail, converts it into electrical signal and transmits it to engine control unit	Detects wrong temperature	Wrong fuel temperature compensation disturbed performance of engine	Temperature sensor damaged (mechanically)	2	5	6	60	
	Wrong conversion temperature to electrical signal		Wrong calibration					
	Transmits wrong (or no) signal to engine control unit		Electrical failure (broken cable, shortcut to ground, loose contact)					

BE 0472
App. A11

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
3.2.3 Engine control unit								
Fu. 1: Controls duration of injection (=fuel metering) as function of driver demand, speed, fuel temperature	Disabled control	Disturbed engine operation (performance) and safety hazard (e.g. speed, cylinder pressure, exhaust gas temp. too high)		2	10	2	40	
Fu. 2: Controls engine speed (max. speed, idle speed)	Disabled control	-- " --						
Fu. 3: Limits full load quantity (as function of speed)	Disabled control	-- " --						
Fu. 4: Controls injection timing (as function of temperature, speed, injection duration)	Disabled control	-- " --						
Fu. 5: Controls start quantity	Disabled control	-- " --						

BE 0472
App. A12

System/item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation O	I	D	RPN	Comments
4.(C) Fuel control system								
4.1 Solenoid valve V1; (2 position / 3 way valve)								
Fu. 1: Fuel supply shut off (not powered) cl.SE, cl.SD, op.ED	op.SE, cl.SD, cl.ED	Uncontrolled filling of fuel system	Valve body hangs in open SE position (mechanically)	2	6	8	96	
			Valve powered (e.g. short cut to ground)					
	op.SE, op.SD, op.ED	Short circuit storage to purge tank and uncontroled filling of fuel system	Valve body hangs between seats	6	10	8	480	Filter in supply line ! Take care on seals at valve body !
			Leakage					
	cl.SE, cl.SD, cl.ED	Filling and purging of system is disabled	Blocked by particles	2	7	2	28	
Fu. 2: Fuel supply switched on (valve powered) op.SE, cl.SD, cl.ED	cl.SE, cl.SD, op.ED	No fuel supply	Valve not powered (electrical failures)	5	7	2	70	
			Valve body mechanically blocked					
	op.SE, op.SD, op.ED	see Fu. 1					s.a.	
	cl.SE, cl.SD, cl.ED	see Fu. 1					s.a.	
4.2 pr2 (mechanical pressure valve)								
Fu. 1: Enables fuel circulation (from c_p) into rail, supply of cool fuel to injectors - open SE	Closed SE	Uncontrolled built up of residual line pressure - if NOP is reached -> fuel injection !	Valve body hangs in closed SE position (mechanically)	2	10	8	160	Safety valve for circulation pump (max pressure limitation) !
Fu. 2: Controlls residual pressure in control line and injectors -> pressure difference between SE controlled by spring	Pressure difference between SE lower than specified	Residual pressure in injectors too low, partial evaporation of fuel, reduced engine power output	Valve body hangs in open SE position (mechanically)	7	5	8	280	
			Broken spring					
	Pressure difference between SE higher than specified	No effect	Valve body hangs at position with too small flowares (mechanically)					
			Pieces and particles reduce flowares					
			Leakage					

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
4.3 hp_epr (electronical pressure regulator)								
4.3.1 actuator (solenoid controled orifice)								
Fu. 1: Controlls pressure in high pressure rail by returning the surplus fuel, which is delivered from high pressure pump into rail -> open SE (open orifice if actuator not powered)	Orifice SE too small	Uncontrolled pressure increase in high pressure rail	Valve body hangs in position with too small flow area for SE (mechanically)	2	10	8	160	An indicator is easy to install because pressure sensor is already in system ! Indicator would lower D !
			Orifice blocked by particles					
			Electrical drive for solenoid too high					
	Orifice SE too large	Pressure in high pressure rail does not reach the desired level	Valve body hangs in position with too large flow area for SE (mechanically)	4	7	3	84	
			Leakage					
			Bouncing of valve body					
			Electrical drive for solenoid too low					
4.3.2 pressure sensor for hp_epr								
Fu. 1: Detects pressure in high pressure rail, converts it into electrical signal and transmits signal to pressure control unit	Detects wrong pressure	Uncontrolled pressure in high pressure rail, same effects as 1.6.1	Pressure sensor damaged (mechanically)	2	10	8	160	Install overpressure relieve valve !
	Wrong conversion pressure > electrical signal		Wrong calibration					
	Transmitts wrong (or no) electrical signal to control unit		Electrical failure (broken cable, shortcut to ground, loose contact)					
4.3.3 electronic pressure control unit								
Fu. 1: Receives electrical signal from pressure sensor and receives desired pressure -> calculates electrical drive for actuator and transmitts this data to actuator	Detects wrong signals	Uncontrolled pressure in high pressure rail	Electronic hardware or software failures in control unit	2	10	8	160	Install overpressure relieve valve !
	Calculates wrong drive data for actuator solenoid							
	Transmitts wrong (or no) electrical drive data to actuator solenoid		Electrical failure in cable to actuator (broken cable, shortcut to ground, loose contact)					
	No electric power supply		Electrical failure in power supply (broken cable, shortcut to ground, loose contact)					

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
4.4 fuel system control unit								
Fu. 1:Key off>on (change state from "park" to "ready for start")	Does not change state	V1 not switched ON	Failures in hardware + software of fuel CU, disconnection of component (cable, connector)					No numbers were specified because system components (e.g. V1) individually assessed !
		Fuel supply pump not switched ON	--- " ---					
		Circulation pump not switched ON	--- " ---					
		Rail pressure CU not switched ON	--- " ---					
		Purge press. CU not switched ON	--- " ---					
		Engine CU not switched ON	--- " ---					
Fu. 2:Key off>on (change state from "pending for shutdown" to "ready for start")	Does not change state	Fuel supply pump not switched ON	--- " ---					
		Circulation pump not switched ON	--- " ---					
		Rail pressure CU not switched ON	--- " ---					
		Purge press. CU not switched ON	--- " ---					
		Engine CU not switched ON	--- " ---					
Fu. 3:Key on>off (change state from "ready for start" to "park")	Does not change state	Fuel supply pump not switch. OFF						
		Circulation pump not switch OFF	--- " ---					
		Rail pressure CU not switch OFF	--- " ---					
		Purge press. CU not switch OFF	--- " ---					
		Engine CU not switched OFF	--- " ---					
Fu. 4:Pending time exceeded (change state from "pending for shutdown" to "park")	Does not change state	V1 not switched OFF	--- " ---					
Fu. 5:Key on>start (change state from "ready for start" to "crank engine")	Does not change state	Starter motor not switched ON	--- " ---					
Fu. 6:Key start>on & engine not operating (change state from "crank engine" to "ready for start")	Does not change state	Starter motor not switched OFF	--- " ---					
Fu. 7:Key start>on & engine operating (change state from "crank engine" to "engine operation")	Does not change state	Starter motor not switched OFF	--- " ---					
Fu. 8:Key on>off & engine operating (change state from "engine operation" to "pending for shutdown")	Does not change state	Fuel supply pump not switch. OFF	--- " ---					
		Circulation pump not switch OFF	--- " ---					
		Rail pressure CU not switch OFF	--- " ---					
		Purge press. CU not switch OFF	--- " ---					
		Engine CU not switched OFF	--- " ---					

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
5.(C) Auxiliary Components								
5.1 hp_p (high pressure pump)								
Fu.1: Builds up rail pressure	Not capable to build up rail pressure	Reduced power output	Failures in hydraulic part of pump (valves, plungers, sealings, etc.)	6	7	3	126	New technology !
		If pressure below a certain limit (approx.NOP) engine cannot be operated	Mechanical failures in pump drive					
5.2 c_p (circulation pump)								
Fu. 1: Produces residual pressure in injectors	Not able to produce the desired residual pressure	Residual pressure in injectors too low, partial evaporation of fuel, reduced engine power output	Failures in hydraulic part of pump (valves, plungers, sealings, etc.)	6	5	5	150	New technology !
			Mechanical or electrical failures in pump drive					
Fu. 2: Enables fuel circulation in rail for cooling purpose	No (or too low) fuel circulation	Uncontrolled heating of fuel, partial evaporation of fuel, unstable fuel injection, reduced power output	Failures in hydraulic part of pump (valves, plungers, sealings, etc.)	6	5	5	150	
			Mechanical or electrical failures in pump drive					

System/Item Component Functions	Potential failure	Effect of failure	Cause of failure	Evaluation				Comments
				O	I	D	RPN	
5.3 Purge tank pressure control system								
5.3.1 Compressor								
Fu.1: Delivers DME from purge tank into storage tank	Does not deliver DME from purge tank into storage tank	Pressure in purge tank increases, reaches saturation pressure, condenses, tank filled with liquid DME	Mechanical failures in compressor or compressor drive	2	10	10	200	
			Failures in power supply to compressor (electric, pneumatic...)					
5.3.2 Pressure sensor for purge tank pressure control system								
Fu.1: Detects pressure in purge tank and transmits signal to pressure control unit if a maximum or a minimum value is reached	Does not detect maximum pressure	Compressor is not actuated, see 5.3.1. Fu.1	Pressure sensor damaged (mechanically)	2	10	10	200	
			Wrong calibration					
			Signal (electric or pneumatic) not transmitted to pressure control unit (broken cable or hose, loos contact etc.)					
	Does not detect minimum pressure	Compressor is continuously working and evacuates purge tank	Pressure sensor damaged (mechanically)					
			Wrong calibration					
			Signal (electric or pneumatic) not transmitted to pressure control unit (broken cable or hose, loos contact etc.)					
5.3.3 Purge tank pressure control unit								
Fu.1: Receives signal for maximum purge tank pressure and actuates compressor	Misinterpretation of signal	Compressor is not actuated, see 5.3.1. Fu.1	Mechanical, electrical, pneumatical failure in controller	2	10	10	200	
	Does not actuate compressor		Failure in signal transmission to compressor power supply (electronic, pneumatic)					
Fu.2: Receives signal for minimum purge tank pressure and stops compressor	Misinterpretation of signal	Compressor is continuously working and evacuates purge tank	Mechanical, electrical, pneumatical failure in controller					
	Does not stop compressor		Failure in signal transmission to compressor power supply (electronic, pneumatic)					

Advanced Engine Technology Ltd.

Diesel Engine and Component Test/Research Facility

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